PROCEEDINGS

11th INTERNATIONAL SPACE SYNTAX SYMPOSIUM

SSS LISBON

3 - 7 JULY 2017

PROCEEDINGS OF THE 11TH INTERNATIONAL SPACE SYNTAX SYMPOSIUM

EDITORS

Teresa Heitor
Miguel Serra
João Pinelo Silva
Maria Bacharel
Luisa Cannas da Silva

DESIGN

Pixel Reply Lda. / www.pixelreply.com
Luísa Cannas da Silva e Maria Bacharel
Golpe de Estado

PUBLISHER

Instituto Superior Técnico, Departamento de Engenharia Civil,
Arquitetura e Georrecursos, Portugal

ISBN

978-972-98994-4-7

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JEAN WINEMAN
Taubman College of Architecture and Urban Planning, University of Michigan, USA

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3D-INFORMED CONVEX SPACES

The Automated Generation of Convex Representation for Open Public Space Analysis

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LJILJANA CAVIC
CIAUD, Faculty of Architecture , University of Lisbon
ljiljana.cavic.arh@gmail.com

RUSNE SILERYTE
CIAUD, Faculty of Architecture , University of Lisbon
rusne.sileryte@gmail.com

JOSÉ NUNO BEIRÃO
CIAUD, Faculty of Architecture , University of Lisbon
jnb@fa.ulisboa.pt

ABSTRACT

Studies on open public spaces are based on representational models that can until some extent encompass their intrinsic complexity involving some simplification of reality based on tractability purposes and research interests. In order to construct a representational model for analysis of open public spaces the paper proposes an automated method for space compartmentalization into unique convex non-overlapping spatial units aiming at preserving most of the available structural and semiotic data which could be further visualized and organised in more flexible manner. It addresses the representational issues of open public spaces starting by convex spaces representation, as defined by Space Syntax methodology, looking at its strengths and weaknesses regarding the robustness of rules, sensitivity to tri-dimensional context and importance of topography.

Based on that, a 3D-informed algorithm for convex spaces' construction is divided in two main parts: (a) space triangulation; and (b) triangle aggregation for convex space generation. The first part encodes tri-dimensional urban limits, vertical, horizontal and topographical which are further used as the basis for triangulation. The second part allows for triangles' aggregation into convex spaces according to convexity thresholds and a function of space superiority or dominance.

Finally, the analytical applicability of the model is demonstrated on the case study of riverside Lisbon whence some advantages of 3D-informed map in comparison to other representational models, such as VGA, RCL and Space Syntax's convex space model are pointed out. In addition, some applications of the new 3D-informed convex map are presented: a) the map makes part of a broader versatile data model; b) the proposed 3D-informed convex spaces are used as the basis for tri-dimensional representational models of Convex, Solid and Fragmented Voids whose generative algorithms are briefly presented.

KEYWORDS

Open Public Spaces; Convex Space Representation; Convex Voids; Solid Voids; Fragmented Voids; Analytical Models

1. INTRODUCTION

Recently urban studies give priority to spatial phenomena such as movement, visual fields, networks, etc. More traditional approaches which account for relationship between urban morphologies and stationary usages of public spaces are to some extent neglected. In that regard, the paper puts into focus representation of open public spaces as individualized spatial entities or 'open rooms' intended for sojourning. Even though convex spaces, as defined by Space Syntax, seem to be able to capture open public spaces as individualised spatial phenomena, several representational issues, such as lack of robust automated procedure, excessive simplification of data and incapacity of model to capture basic urban entities, such as streets, diminish their usability. For that purpose we propose an enhanced convex spaces representation which aims at preserving most of the available data which could be further visualized and organised in more flexible manner. In short, 3D-informed convex spaces are an automatized user- guided convex space representation which on one side encodes structural and semiotic information of individual compartments of open public spaces, and on another, preserve topological relationship of the system as a whole.

Shortly, in urban environment, open public spaces form continuum but on the other hand are individualised yet interconnected spatial entities. The presented research stems from the need of studying unbuilt part of open public spaces and finding a discretized representational model that would be able to capture open public space, both as an individual spatial entity and part of a broader network, and analyse its main attributes in a consistent and automated manner. Considering that one of the main tasks in this research is to gather understanding on the properties of open public spaces as intermittently apprehensible spatial compartments, the convex space representation from the Space Syntax theory (Hillier and Hanson, 1984) seemed to some extent a suitable representation model. However, this representation model also contains the inconsistencies and insufficiencies mentioned above that need to be addressed before one can concentrate on the particular problems of open space attributes and qualities. This is particularly crucial at local scales like neighbourhood or simply individual public space analysis.

1.1 METHODOLOGY

In this paper we embraced the task of developing an algorithm for a robust and automated representation of open public spaces - 3D-informed convex spaces – that, by accounting for tri-dimensional data and allowing for further generation of multi-layered urban void representations, overpass some inconsistencies of the convex spaces as defined by the Space Syntax theory. Moreover, by concentrating on individual morphological qualities of open public spaces as framework for stationary and sojourning activities, they allow for spatial analysis mostly neglected by network and movement oriented approaches that on the other hand, by preserving topological relationships of the system as a whole are still possible.

The work is divided into the following parts:

- 2.0 Implementation
  - 2.1 Usability of convex spaces representation in urban studies
  - 2.2 Discussion on Space Syntax convex spaces representation
  - 2.3 Theoretical bases of 3D-informed convex map
  - 2.4 Algorithm for 3D-informed convex map
- 3.0 Results
  - 3.1 Analytical applicability and advantages of 3D-informed convex map
  - 3.2 Further application of 3D-informed convex map

2. IMPLEMENTATION

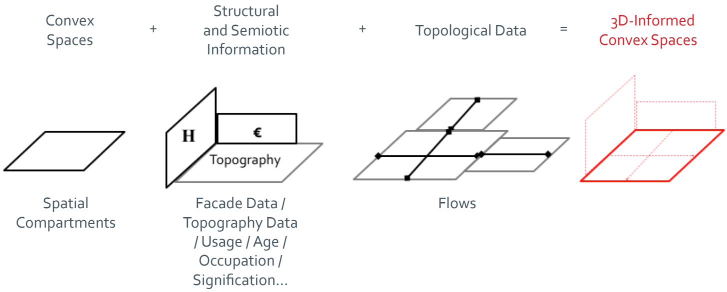
2.1 USABILITY OF CONVEX SPACES REPRESENTATION IN URBAN STUDIES

Urban void is a continuum nevertheless divided into smaller places which, as separated units, could be perceived while wandering about the city. Diversity in scales and sizes, revelation of new visible scenes, passage through porches, are some possible brake-triggers in the continuity of open public spaces' apprehension. Mental compartmentalization of space has been explored by Gestalt psychology claiming that such conditions as proximity, similarity, closed form or contour, regularity, symmetry, inclusiveness, harmony and maximal simplicity play an important part in organizing visual field into independent units (De Jonge, 1962). Searching for limits and organizing elements into meaningful objects is deemed an important evolutionary mechanism of human brain which make possible enemy to be recognized from distance even if only partially seen (Ramachandran and Hirstein, 1999). These mental representations suggest that the compartmentalization technique that is commonly used to separate multiple parts of a system into meaningful subsystems for the purpose of simplification can be useful in structuring spatial representations.

As deliberate simplifications, representational models of reality allow for their tractability (Frigg and Hartmann, 2012) but the character of such models tend to accommodate particular forms of simplification that should be suitable for particular forms of analysis. In other words, specific types of representation models are more adequate for specific types of analysis simply because they emphasize or give evidence to that specific type of knowledge or properties of the model. For instance, graph models are proven robust models for the representation of the large urban street networks (Jiang and Claramunt, 2004), movement patterns forecast (Hillier and Iida, 2005) or visual studies (Turner et al., 2001), but they are not explicative for morphologic or shape-based studies of directly embodied built environment.

On the other hand, even though convex spaces representation is based on spatial compartmentalisation and takes into account important formal qualities of built environment, there are few studies which employ this representation in analyses of outdoor spaces. Nevertheless, the insight they give into morphological capacity of open public spaces to provide framework for sojourning and stationary activities is deemed important (Anter and Weilguni, 2013) and it is neglected in more widely used representations such as axial, graph, Road Central Lines (RCL) or Visibility Graph Analysis (VGA).

Since we recognize the importance of focusing on open public spaces as individualized compartments that can preserve their underlying network and field structure, we proposed an enhanced 3D-informed convex representation which allow for encoding of data from tri-dimensional context and topography in a robust way. The encoded data stays linked to convex spaces representation and can be withdrawn depending on analysis type and scale.



Apart from being useful for visualisation and analysis of individual open public spaces in relationship to their direct boundaries and regarding their positioning within a broader urban network, convex representation permits for more efficient data organisation and manipulation. By convex compartmentalisation, the model permits delimitation for data examination and more prompt analysis by avoiding redundant processing.

2.2 SPACE SYNTAX CONVEX SPACES

Even though, convex maps as defined by Space Syntax (Hillier and Hanson, 1984), emphasises the isolated character of spaces providing a representation where spaces can be analysed individually or in relation to others, there are several weaknesses that can be pointed out such as: robustness of rules resulting in lack of automated procedure, excessive simplification of data, neglecting of tri-dimensional and topography information and incapacity of model to capture basic urban entities, such as streets.

The lack of automated procedure is a result of ambiguity of interpretation of spatial limits observable in non-traditional urban tissues. Although the convex space representation seems quite straightforward when addressing traditional urban structures such as the one of Parma where the well-defined spaces are rather obvious and easy to capture, several difficulties or ambiguities arise in other types of urban structures such as the modern city, iron grid tissues and dispersed urban spaces (figure 1). Modern grids and dispersed tissues present the difficulty of dealing with unbounded space where public space loses the affinity with open space within ceiling-less rooms (as one might have about those of the traditional city) and the built form becomes frequently isolated and surrounded by continuous undefined space. In those situations, convex space boundaries become loose thus the representation of convex spaces turns into an ambiguous task. We can easily observe that the more ambiguous the boundaries of an area, the bigger we have the chances to get different interpretation (or representations) of the same space from different (specialist) observers. Even in traditional spaces and especially in large study areas we are likely to get two different convex maps from any two persons drawing them even if they are equally knowledgeable on the subject and study area.

In that sense, the presented automated procedure (see section on Algorithm for 3D-informed convex map) allows for flexible yet replicable method whose outputs when generated with the identical parameters would be the same.

Figure 1 - Traditional vs. Modern Grid, Parma vs Le Corbusier's project for Saint-Dié, from "Collage City" by Rowe and Koetter

Moreover, in iron grid tissues, the algorithm as defined by Space Syntax produces a continuous long space along the largest streets while leaving the orthogonal streets broken into separate spaces even though they might be aligned in the same way as the perpendicular ones are. Even though the Space Syntax model captures the difference between the main streets and secondary streets, in the convex representation as we propose it, all street crossings correspond to single convex spaces. In that way, they become amenable to be aggregated in either direction as continuous streets, which seem a much more accurate representation of the natural ambiguity of the iron grid where flow can potentially occur along any direction.

Furthermore, the convex map, as given by Hillier and Hanson is a flat, bi-dimensional representation, reflecting almost no information on the topographical qualities of urban spaces namely distinct levels in a square, openness in belvederes, open views along steep streets, streets going up and down, etc. Such issues become even more important and complex if we want to address the effect of the architectural containment of space defined by buildings surrounding public spaces. In that case, information about building height is essential since, together with the width of streets, it could produce a perceptual virtual ceiling which might give us an expression of how much surrounding buildings contribute to the feeling of containment.

Considering the above-mentioned weaknesses of Space Syntax convex map we developed a 3D-informed convex space representation able to capture the mentioned ambiguities and subtleties of space which could bring new insights or simply produce more robust analytical models to address the complexities of open public spaces.

2.3 THEORETICAL BASES OF 3D-INFORMED CONVEX MAP

The important postulate for construction of 3D-informed convex spaces is importance of tri-dimensional changes within built environment which participate in chunking of urban void. Explicit changes in structure of built envelope, such as those that occur in streets' crossroads obviously isolate these spatial units one from another allowing for their further grouping by enabling both streets, which make part of the crossroad, to be further unified as urban entities. Apart from the obvious tri-dimensional changes, there are situations where break in continuity of built envelope occurs only on one side of the space thus the discontinuity between units is not as explicit as in crossroads' examples. These visual cues do not constitute explicit physical boundaries, but due to their mutual proximity nevertheless establish visual relationships which lead towards their interpretation as boundaries (Meiss, 1990). As claimed by the Gestalt theory, human mind usually searches for the regularity within visual fields, thus mental representations of space are commonly associated with geometric shapes. Even if a space is not clearly outlined by explicit limits, human mind tends to recreate them using other cues within the system as visual references. These implicitly induced limits are found important in space compartmentalization and as such introduced in the proposed methodology and further used for 3D-informed spatial compartmentalization. The definition of Implicit Limits and their encoding is in more details explained in the following section on Algorithm for 3D-informed convex map.

Taking into consideration compartmentalization as important in spatial apprehension together with explicit and implicit tri-dimensional information found in built environment we proposed an extension of convex spaces, as defined by Space Syntax, into an automated 3D-sensitive and user-guided representational model. Differently from the Space Syntax method which provides the smallest number of fattest convex spaces (Hillier and Hanson, 1984), our 3D-informed subdivision by introducing implicit limits aims at gathering a minimum number of elements that allow the maximum number of possibilities for aggregation (Beirão, Chaszar and Cavic, 2014, 2015). On one hand, these drawing principles account for changes in built environment and on the other permit convex spaces' aggregation into more complex spatial entities.

2.4 ALGORITHM FOR 3D-INFORMED CONVEX MAP

The translation of the Space Syntax method for generating convex maps as described by Hillier and Hanson (1984) into an automated process is considered difficult (Carranza & Koch 2013). Even though computational geometry addresses the problem of convex partitioning of polygons

as one of the basic problems (Preparata and Shamos, 1985), the subdivision of a polygon with holes (Lingas, 1982) or those relevant from a spatial analysis perspective (Carranza & Koch 2013) are deemed challenging. The method based on the medial axis transform developed by Carranza & Koch (2013) is suitable for subdividing architectural plans into non-overlapping, convex partitions, but it accounts merely for the 2D geometry of building footprints.

Based on the mentioned gaps, we developed a method for the compartmentalization of the continuous urban void based on 3D visual information defined by explicit and implicit physical and perceptual limits of urban environments. As the starting input, we use geometric data that contain semantic attributes and absolute measures of height. The data are manually structured into: Horizontal limits (ground and overhang) and Vertical limits (planar and volumetric).

2.4.1 INPUT DATA - URBAN LIMITS

Horizontal limits

Ground limits are constant horizontal boundaries that include elements such as topography, streets, pavements which are a horizontal bottom of urban void only approachable from the upper side.

Differently, *Overhang limits* are horizontal discrete limits such as bridges, shadings, publicly accessible roofs, etc., which can be apprehended from the bottom and upper side thus can delimit two vertically overlapped voids (such as those that one can find under and above bridges).

Vertical limits

Planar limits account for linear elements such as fences and walls that can be approached from both sides and as such divide urban voids into smaller compartments

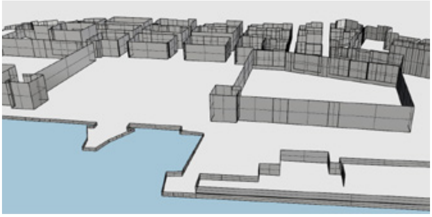
Volumetric limits such as buildings and water surfaces are approachable only from outside thus define certain unapproachable area within urban voids.

Implicit limits

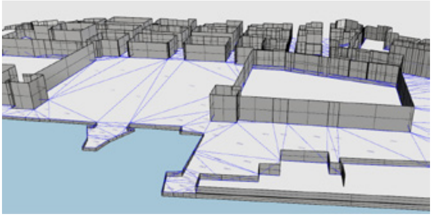
Apart from Horizontal and Vertical limits extracted from the initial 3D model, the method introduces the notion of Implicit Limits which as visual cues participate in spatial compartmentalization. Using Meiss' theory on limits, implicit ones can be explained as visual cues that do not constitute continuous and uninterrupted boundary, but due to proximity allow for establishing visual relationships which further lead towards unified interpretation (Meiss, 1990). While the explicit changes in height of built environment, such as those that occur in crossroads, clearly partition urban voids, there are situations in which changes in built environment height occur only on one side of the space. These separations or discontinuities, as termed by Peponis et al. (1997) are not as straightforward as in crossroads' examples but they are nevertheless important in chunking urban voids and as such addressed in the proposed methodology.

Automated procedure

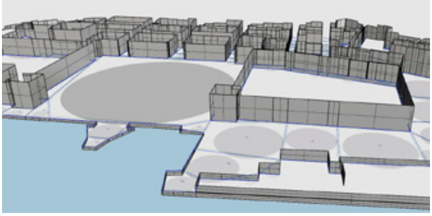
In short, the computational aspect of automated procedure begins with 3D model of Urban Limits e.g. buildings, fences, water and other elements that obstruct either line of sight or locomotion. Further, these are encoded (horizontal urban limits separated into ground and overhang; vertical urban limits - planar and volumetric) into the main spatial taxonomies (location, spatial vertex, spatial edge) which account for both implicit and explicit limits. Later those limits are fed into the process of Delaunay's triangulation that produces robust spatial units - triangles, which are further aggregated into unique non-overlapping compartments - convex spaces, as explained further on.



Urban Limits



Triangles



3D-informed Convex Spaces

Figure 2 - Urban Limits > Triangles > 3D-informed Convex Spaces

2.4.2 TRIANGULATION AND MERGING TRIANGLES INTO 3D-INFORMED CONVEX SPACES

As previously explained, the set of implicit vertices together with the explicit ones are used for spatial triangulation using Delaunay's algorithm. The triangles are later joined into 3D-informed convex spaces using region growing algorithm based on the convexity thresholds and the function of superiority. The rules for triangle merging were:

1. Separate compartments must be convex within a given threshold decided by the user, where horizontal convexity is measured as ratio between the area of the space and its convex hull;
2. Convexity is measured horizontally and vertically meaning that each point of a lower limit must be observable from each other point of the space, elevated from the lower limit (topography) by a single person's height;
3. If one Triangle can belong to multiple compartments that comply to the above-mentioned rules, the priority is given to the one that has a higher value of superiority[1]

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[1] The value of superiority indicates how much a certain convex space is likely to dominate above the others to be perceived as a separate one. Hillier and Hanson (1984) have suggested that superiority should be measured as a value of fatness, however, that does not account for the shape of a space, while two rectangles of the same width and different length have the same value of fatness.

In order to find all the possible convex spaces a dynamic region growing algorithm was used, so that computation time could be significantly reduced. The algorithm uses all Triangles as initiation entities for recursive growing in every direction until no Triangle can be added to keep the space convex. All the solutions are cached in a memory-based data structure to avoid redundant computations. Based on their superiority, all the possible convex spaces are ordered, sequentially choosing the most superior one and eliminating the ones that it overlaps with until no more spaces are left. The chosen set of spaces compartmentalizes the urban void under investigation into unique non-overlapping convex partitions generating a so-called 3D-informed convex map.

2.4.3 MODEL FLEXIBILITY AND ADAPTABILITY

The construction procedure of 3D-Informed convex map is automated, yet flexible, adaptable and user-guided as a result of several parameters that could be adjusted due to specific theoretical backgrounds. Apart from the choice of input data whose preselection and granulation necessarily accounts for specific research premises, other parameters especially those linked to the model precision and definition of implicit limits are also controllable.

Model flexibility and adaptability regarding Granularity and Content:

1. The granularity and content of model depends on information available but can also be filtered regarding type or scale of analysis.
2. Ideally, the model should contain as many elements as available, from smaller urban design scale towards larger urban elements which could be further filtered and selected from. The introduction of semiotic qualities (e.g. usage of buildings, price of real estate) and temporal qualities of limits (e.g. there are limits which exist only during certain period of day such as gates which are closed during night) useful for event-based modelling is also taken into account.

Model flexibility and adaptability regarding what Implicit Limits (figure 2) should be taken into consideration, the code allows adjustment of the several parameters:

1. The maximum distance in which the influence of the implicit points (vertices) should be searched for - Search Space.
2. The significance precondition of explicit limits to get projected as implicit ones, defined through the bearing angle, vertices' height difference and vertices minimum horizontal distance - Attribute of significance.
3. If found within the predefined search boundaries (1), with satisfied attributes of significance (2), the explicit limits are projected by rectangular offsetting over the edge forming so called implicit vertices.
4. Finally, based on a given tolerance value the nearby vertices are collapsed into a single vertex in order to avoid formation of tiny triangles. Only implicit vertices are collapsed giving priority to the explicit ones - Tolerance value.

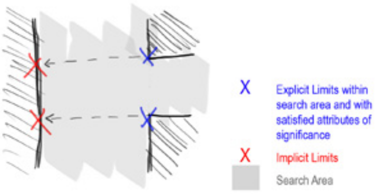


Figure 3 - A sketch that explains construction of Implicit Limits

For example, in the chosen case of Riverside Lisbon, the Search Space which we established as meaningful for checking of existence of significant vertices was defined due to the widest street dimension. In this way, the vertices from one to other side of the wide street would still be considered influential. In the case study of central riverside Lisbon, the wall structure of the widest street Avenida 24 de Julho which is cc 50m wide, had to look for its projected implicit vertices. Since the Search Space is defined as multiplier of the limit length and the shortest limit is around 5m long the multiplier of 10 was chosen. Further, it was needed to define which vertices are significant enough to get projected which was defined regarding the bearing angle (minimum 30º) and the difference between neighbouring vertices (minimum 3 meters, approximately 1 floor). In this way, the projectable vertices were selected. Finally, all projectable vertices found within pre-established searching area were tested for their proximity and cleaned up whenever the 5 meters' proximity tolerance was not respected.

3. RESULTS

3.1 ANALYTICAL APPLICABILITY OF 3D-INFORMED CONVEX MAP

The capacity of 3D-informed convex spaces to preserve data about belonging facades, flows, topography (Table 1) facilitate their comparison and information overlaying allowing for multidimensional analyses of open public spaces.

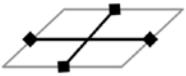
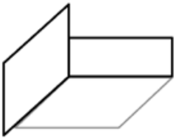
3D-informed Convex Space	Short Name	Name	Property
Convex Spaces 	**CS_Id**	Convex Space	ID attributed to Convex Space
	CS_Area	ID	CS Area calculated from the area of all belonging triangles
	CS_Per	Convex Space	CS Perimeter calculated as length of 3D circumferential polyline
	CS_Circ_Diam	Area	Diameter of the biggest circle inscribed inside CS
	CS_Elev	Convex Space Perimeter	Topographic elevation of convex spaces
	CS_F_Cast	Convex Space Circle Diameter	ID of Flows which belong to CS
	CS_Fac_Cast	Convex Space Elevation	ID of Facades which belong to CS
Flows 	**F_ID**	Flow IDs	ID attributed to Flows
	F_Length	Flow Length	Flow Length calculated in 3D
	F_Inclin	Flow Inclination	Flow inclination calculated in XZ plane
Facades 	**Fac_ID**	Facade IDs	ID attributed to Facades
	Fac_Height	Façade Height	Façade Height calculated from front orthographic projection
	Fac_Area	Façade Area	Façade Area above the topography mesh
	Fac_Width	Façade Width	Façade Width calculated from top orthographic projection
	Fac_Proportion	Façade Proportion	Façade Width / Length ratio

Table 1 - Data embedded in 3D-informed Convex Spaces

This means that differently from some other representations such as Space Syntax convex spaces, VGA or RCL which concentrate on one dimension of spatial entities, either formal, visual field or central road line, 3D-convex map permits visualisation and further interpretation of various spatial attributes and properties. Among many, one can observe attributes such as:

- Overall diversity of built structure expressed through number of façades per space or 100m of space perimeter
- Average height of buildings that belong to certain Convex Space
- Spatial linkage expressed by number of flows or entrances within Convex Space
- Length of flows within specific Convex Spaces which give an insight into length of walkable route
- Etc.

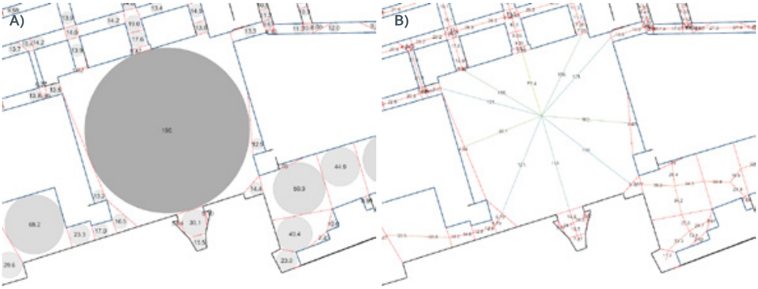


Figure 4 - 3D-informed convex map properties – A) Maximum inscribed circle, B) Flows length

As demonstrated, 3D-informed convex map preserves data of tri-dimensional built and topographic surroundings, together with location and network information. It therefore allows for multidimensional analysis by combining various level of information. Moreover, convex compartmentalisation permits meaningful delimitation and of specific open public space or certain radius of vicinity that facilitates data examination, analysis replication and acceleration by avoiding redundant processing.

Regarding the highlighted differences between Convex Maps as defined by Space Syntax and the proposed 3D-informed convex map as an automated alternative here presented, several advantages were inferred regarding the criteria presented in the table 2. Namely:

- 3D-informed convex space accounts for a more complete set of spatial data because they take into consideration tri-dimensional information of topography and built environment heights, disregarded in Space Syntax convex maps.
- 3D-informed convex map accounts for cognitive ability of human brain to search for complete objects with uninterrupted limiting boundaries, wherefrom a necessity for implicit limits definition originated. The conceptualisation of implicit limits is straightforwardly defined which permitted automation of proposed drawing procedure. However, definition of Implicit Limits is flexible and user-guided allowing for further testing and fine-tuning of procedure.
- Even though automated, the procedure is user-guided and flexible. Several parameters such as: threshold of convexity, search space for implicit limits, significance of can be chosen by user depending on research objectives.

- Because it takes into consideration streets crossings, 3D-informed convex map allows for several aggregation possibilities between convex spaces which further could be visualised and represented through various outputs, ex.: central street lines, possible paths between spaces' edges, graphs, etc.
- Since 3D-informed convex spaces preserve data about surrounding limits, information about unbuilt space and correspondent built surrounding can be compounded and compared.
- Behind morphological properties additional semiotic descriptors can be added to the model. Data such as age, material, usage, thermal properties, etc. can be added to the representation of physical structures.
- Due to topography and location information preserved in 3D-convex spaces, they can be used for two types of accessibility analysis separately addressed by two Space Syntax approaches: geometric or space accessibility (addressed by axial maps) and geographic or place accessibility (addressed by convex spaces). If we take into consideration the possibility for addition of semiotic descriptor to the morphological entities, the importance of attractions point in the measuring accessibility can be also assessed.

Criteria of comparison	Space Syntax Convex Spaces	3D-informed Convex Spaces
Input Data	2D map	3D model
Input Elements	Urban-architectural Boundaries	Explicit limits: Urban-architectural Boundaries, Topography Implicit limits: Projected edges from close neighbourhood boundaries due to their influence: distance and height
Drawing procedure	Drawing procedure is ambiguous. Two different persons tend to draw a different convex map of the same area.	Drawing procedure is bottom-up, automated and flexible. The parameters of convexity might be defined manifold depending on research objectives and background theory adopted.
Possible additional outputs	No additional outputs presented till today.	Aggregation Maps, 3D Models of Convex, Solid and Fragmented Voids (see following section) Central Street Lines, Paths map, Graph

Table 2 - Comparison between Space Syntax Convex Spaces and 3D-informed Convex Spaces

3.2 FURTHER APPLICATION OF 3D-INFORMED CONVEX MAP

Open public spaces can be seen as a continuous field, a network or smaller portions of urban voids intended for public life, walking, sojourning, etc. Both continuous and discrete conceptualisations of urban voids lead towards separated representations that from diverse stances approach several faces of the same phenomenon - the urban void. The presented convex map makes part of a broader model (figure 4) which allows for different representations and data organisations based on 5 core content concepts of GIS as suggested by Kuhn (2012): location, field, object, network and event.

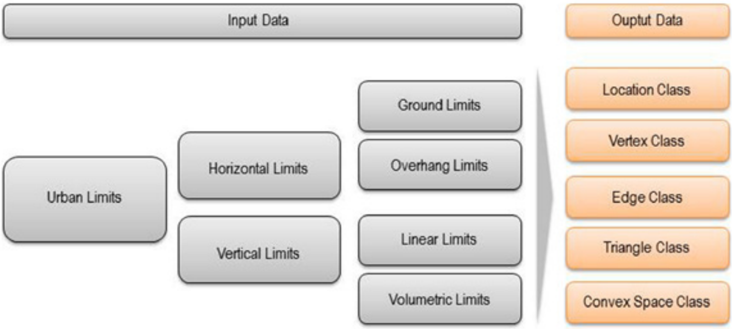


Figure 5 - 3D-informed convex spaces as part of broader representational model

3D-informed convex spaces are object-based constituents which enable further network and event-based modelling. Since the model preserves data about Urban Limits based on which it is constructed, it allows extraction of multi-layered information allowing for comprehensive reading of open public spaces attributes. Built Environment information (building height, elevation, number of entrances, etc.) can thus be combined with attributes of the Unbuilt part (spatial area, shape, inclination, etc.) extracted from the space representation based on either Field, Network or Object conceptualizations. These representations can be either used separately or be mutually combined into multi-dimensional data structures useful for analyses between diverse attributes levels, ex: network properties can be analysed in parallel with object based attributes without necessity for additional modelling or data representation.

3.2.1 POSSIBILITIES FOR FURTHER REPRESENTATIONAL MODELS

Starting from the concept of compartmentalized or object-based data organisation and 3D-informed convex spaces, further tri-dimensional representations can be generated. One of the possible uses of 3D-informed convex spaces has been already addressed (Beirão, Chaszar and Cavic, 2014, 2015) where starting from the convex representation a generation of tri-dimensional open public spaces representation model was proposed (figure 5). These modelling methods termed Convex, Solid and Fragmented Voids allow for encoding and visualisation of tri-dimensional data such as volume and proportion of open public spaces, height of built environment, openness and permeability of spatial limits, etc. on three scales or approximations.

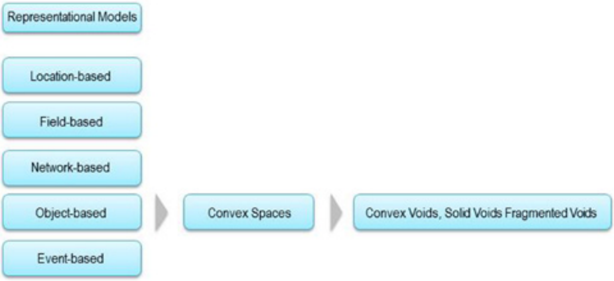


Figure 6 - Possibilities for further representational models

The idea of defining a tri-dimensional representation of open public spaces starts from a convex map representation producing 3D representations called Convex Voids by considering the height of buildings surrounding spaces (Beirão, Chaszar and Cavic, 2014, 2015). These tri-dimensional representations of open public spaces raise questions on how to represent inseparability between the built environment and the in-between urban void. Apart from almost tangible 'urban rooms' which are obviously demarcated by well-defined built limits, there are other somewhat ambiguous cases that need further testing; such as belvederes occupying elevated positions that might be partially surrounded by tall buildings but, although limited physically by a ground containing wall, open visually to an unlimited view towards the horizon as well as a view downhill where the city reveals itself viewed from the top. A question can be put forward: if the height of buildings influences the perception of enclosure raising the height of the Convex Void representation, does the drop-in elevation in the open side of a belvedere influence negatively the representation of the Convex Void? Could we have a kind of negative tri-dimensional representation in some extreme situations?

Convex, Solid and Fragmented Voids representational methods, solidify the unbuilt part of environment by taking into consideration diverse attributes of urban limits. Solidification is applied to convex spaces to generate Convex Voids and can be done according to any chosen properties (highest surrounding limit, average height of surrounding limits, weighted average height of surrounding limits, etc.). Solid Voids are aggregations of Convex Voids based on their vicinity properties - small difference (in length) between the connecting edges and angular deviation of the connection graph below a specified value (as specified in (Beirão, Chaszar and Cavic, 2015). The Solid Voids models consider all possible Convex Voids aggregations and therefore generate a Solid Void network where topological properties can be studied. This model can easily integrate traditional Space Syntax analysis, but also other methods like some proposed by Marshall (2004) and Oliveira (2013). Fragmented Voids consider the fragmentation of a Solid Void by taking into account the model details of the public space that change their perceived chunks of space like trees, areas with different pavements, small barriers like flower beds, benches, sculptures, etc. The fragmented void generation follows similar premises as for CV generation, first by generating a 3D informed space triangulation and then aggregating triangles into convex spaces and then extruding them according to the surrounding objects' heights.

Starting from the same convex map, models of Convex (CV), Solid (SV) and Fragmented Voids (FV) which address different scales of analysis are generated (figure 6). SV typically represent the largest scale of the three and are amenable for neighbourhood studies within the larger city network. CV may be helpful for analytical models at neighbourhood scale and FV represent the finer analysis. The hierarchic relation between these models also establishes a topology between them when composition of one model can be used as an attribute for the entities of the model higher in hierarchy. For instance, a particular SV can be composed by many or few CVs and can be connected to few or many other SVs. Similarly, the number of FVs within a CV gives some information about its granularity, or in spatial terms, how many identifiable sub-spaces can be perceived by the presence of urban objects in a CV (for instance, trees in a uniformly paved square).

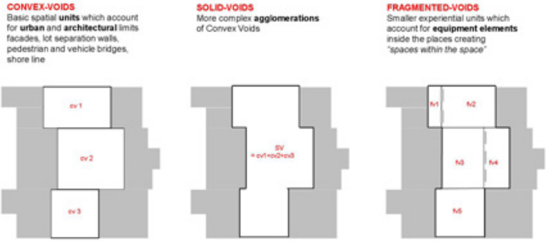


Figure 7 - Possibilities for further representational models – CV, SV, FV

Apart from encoding the 3D information of the built environment, the CV, SV and FV models also permit further introduction of semiotic descriptors. Horizontal and vertical surfaces can be attached diverse non-physical attributes such as ownership type, price, usages, construction date, symbolic values, permitting multi-layer data organization intended for multidimensional spatial analysis.

4. CONCLUSIONS

The suggested 3D-informed convex space representation takes into consideration additional tri-dimensional information usually neglected by other convex map representations such as topographic subtleties and the implicit boundaries. Therefore, it implies bigger number of smaller spatial units which are derived based not only on their two-dimensional representation but the tri-dimensional apprehension. It does so through automated but flexible and user-guided procedure which can further benefit from and be tested by a broader scientific community. Such parameters as definition of Implicit Limits, convexity threshold and function of superiority would especially benefit from testing on other case studies wherefrom some consensus would be expected.

Moreover, 3D-informed convex map preserves information about urban void wholeness and continuity by encoding data on Urban Limits, topography, topological locations, etc. therefore it provides a good basis for multidimensional open public spaces representations and analyses. In that sense, here presented discretized representation makes part of a broader versatile data model which starting by 3D-informed convex spaces as object-based representation also allows for location, field, network, object and event-based model representations. On the other hand, by using compartmentalization procedure the model allows for faster data search, storage and management. Additionally, the 3D-informed convex map can be further used in the generation of Convex, Solid and Fragmented Void representations (Beirão, Chaszar and Čavić, 2015).

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GRASSHOPPER REACH ANALYSIS TOOLKIT:

Interactive parametric syntactic analysis

CHEN FENG
School of Architecture, Georgia Institute of Technology, USA
c.feng@gatech.edu

WENWEN ZHANG
School of City and Regional Planning, Georgia Institute of Technology, USA
wzhang300@gatech.edu

ABSTRACT

Peponis, Bafna, and Zhang (2008) proposed three measures of street connectivity—metric reach, directional reach, and directional distance—to evaluate the potential of access to individual road segment in a street network. A Java program has already been developed at Georgia Tech as an ArcGIS plug-in for calculating the above measures. Although the Java program is suited for analysing large maps coming in GIS file formats, the editing of the input data is often done with other software packages which impedes a smooth dialog between the design exploration and the spatial analysis. We recently developed a toolkit for conducting reach analysis based on the platform of Rhino Grasshopper, allowing users not only to control the various parameters for the analysis in an interactive manner but also to integrate the reach analysis as an essential part of the design formulation process. With the wide recognition and popularity of Rhino Grasshopper for doing parametric design in the design community, this toolkit can also be taken as an analysis component which produces and feeds the result back into the generative component to help find the satisfying or even optimal design solution. This paper explains the data structures and algorithms that we implemented to carry out the various kinds of reach analysis, including details about how we tackled problems encountered in analysing some special street configurations. At the end, it introduces the basic functionalities of the toolkit with a simple example.

KEYWORDS

directional reach, parametric analysis, space syntax, Rhino Grasshopper

1. INTRODUCTION

A range of computational tools has been developed to calculate the measures that are closely associated with or inspired by space syntax theory over the past thirty years. Some of the tools are standalone programs exclusively designed for performing space syntax analysis, such as Depthmap developed by Alasdair Turner at UCL, while some others are extensions to existing CAD or GIS software, such as Spatialist developed by John Peponis's research group at Georgia Tech and sDNA developed by Alain Chiaradia, Crispin Cooper and Chris Webster (Cooper & Chiaradia, 2015; Turner, 2007b). As specialized analytical tools, they share the same workflow: read the input dataset, compute relevant measures, and visualize or output the results in a meaningful way.

Recently, with the generative design approach becoming popular among architects and designers, several attempts have been made to incorporate space-syntax-related measures into the parametric modelling process (Nourian, Rezvani, & Sariyildiz, 2013; Schaffranek &

Vasku, 2013). Integrated with the computational design tools, the space syntax analysis—unlike in the traditional tools—is automated at the back end and the output measures are constantly evaluated to determine how the design should evolve according to a predefined algorithm. Most of the existing tools that fall into this category have been developed as plugins for Grasshopper, a graphical algorithm editor for Rhino.

Acknowledging the growing trend of employing generative design and parametric modelling during the design process and given the popularity of Grasshopper as an effective modelling platform serving that purpose, we developed Grasshopper Reach Analysis Toolkit. The toolkit consists of a series of Grasshopper definitions which not only enables an interactive parametric syntactic analysis but also facilitates communication with other user-defined Grasshopper components to do computational design. We are aware of the several existing Grasshopper tools which are capable of performing space syntax analysis, such as SpiderWeb and Decoding Spaces Components (Bielik, Schneider, & König, 2012; Schaffranek & Vasku, 2013). However, to our best knowledge, the tool presented here is the first Grasshopper plugin developed to compute the reach measures that were proposed by Peponis, Bafna, and Zhang (2008).

In this paper, we explain the data structure and the algorithms that we implemented to carry out the reach analysis. We also illustrate a few scenarios that require special attention through hypothetical examples. In the end, we introduce basic functionalities of the toolkit with a simple real-world example.

2. CONCEPTUAL BASIS FOR REACH ANALYSIS

Specifically, we incorporated the following reach measures in our tool: (1) metric reach, (2) directional reach, and (3) directional distance per length (DDL). The conceptual basis and formal definitions for the above measures can be found in Peponis et al. (2008).

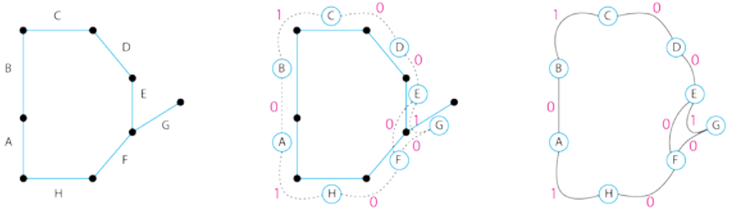
To simply put, the metric reach of a particular point in a given street network can be defined as the street length that is accessible from that point within a specified network distance range. The directional reach of a particular point can be defined as the street length that is accessible from that point within a specified number of direction changes. The DDL of a particular point in the street network can be simply calculated as follows. First, split the total length of the street network into a set of street lengths, with each length representing the amount of street length that is accessible from that point within a certain number of direction changes. Second, factor in the cost of direction change needed to access each portion of street length by multiplying the two together. Finally, add up the weighted lengths and divide it by the total length of the street network.

While we require the input data to consist only of straight lines—as implied by the definition of the directional reach—we used the midpoint of each 'line segment' instead of 'road segment' to compute the average reach measures of a street network. Here, the term 'line segment' refers to one of the smallest straight line segments that the drawing could be deconstructed into, depending on how the drawing is constructed and represented originally. The term 'road segment' refers to the straight line or the chain of straight lines that lie between two adjacent street intersections or that extend from one street intersection but left disconnected at the other end, constituting a dead-end street. The adoption of the line segment as the unit of reach analysis also presents a major deviation from the early version of *Spatialist-Lines*, which is a GIS plugin developed by Zongyu Zhang at Georgia Tech for conducing reach analysis. There are certain advantages and disadvantages associated with this choice. We will explain that later in this paper.

3. DATA STRUCTURE AND ALGORITHMS

We used Dijkstra's algorithm to find the shortest path between the midpoints of two line segments in a given street network (Cormen, Leiserson, Rivest, & Stein, 2009, pp. 658–662). Following the convention for analysing axial-line maps introduced by Hillier and Hanson (1984, pp. 93–94), we abstracted the original street network with a weighted undirected graph in which

each node represented a line segment (or more precisely, the midpoint of a line segment) while the edges represented the connections between those lines. The edge weights were assigned with either the metric distance or the directional distance between two nodes, depending on the type of reach analysis to be performed (Figure 1). We further represented and stored the above information with an adjacency list.



Input street network

Abstracted to a weighted undirected graph

Graph representation of the original network

Figure 1 - Initial graph representation of the original street network. Here the edge weight indicates the directional distance between two nodes.

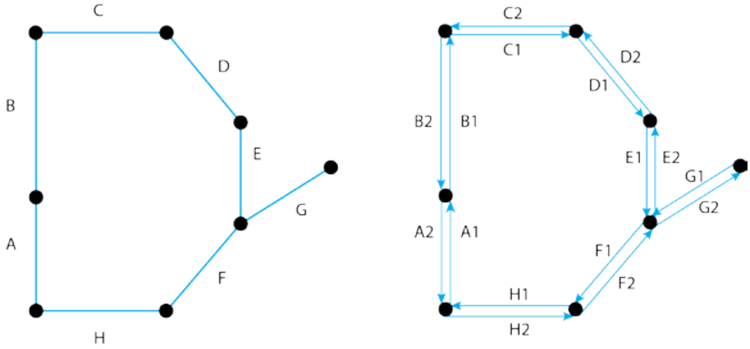
Although the undirected graph has proven to be an effective representation of the original street network in computing the metric reach, it could lead to error when computing the directional reach. Take for example the Y-junction formed by line segments E, F, and G in Figure 1. If we only count a deviation angle that is equal or greater than 90° as a direction change, then given the sharp turn to travel from E to G, one would naturally interpret the directional distance between E and G as one. However, in this case, if without any restriction on directionality, the Dijkstra algorithm would count the directional distance between E and G as zero instead of one because it "thinks" that by taking the alternative route E-F-G (instead of E-G), the sharp turn between E and G at the Y-junction could be avoided. One would immediately see the problem here: there is an implicit assumption that backtracking or making U-turns along F is cost-free.

The assumption is, of course, unjustified and questionable. Turner (2007a) proposed a solution for forbidding U-turns by incorporating 'back' links and 'forward' links for connections at each end of a segment. The way he handled this problem suited the purpose well for the angular segment analysis. However, instead of totally banning U-turns, we preferred to let the cost of taking a U-turn be a variable that could be explicitly controlled. As shown in Figure 2, we converted the original undirected graph into a directed graph as a more general solution.

We generated the directed graph by differentiating the directions of movement on each line segment. Take the line segment A in Figure 2 for example. Assuming the movement is bidirectional on A, we replaced it with two vector-like objects—A1 and A2—with the same endpoints but opposite directions. A1 and A2 are in principle connected, as represented by the two arcs (i.e., directed edges) pointing to each other in the bottom diagrams in Figure 2. However, one can explicitly adjust the cost of those connections (i.e., the cost of making U-turns) by assigning different edge weights onto those arcs. The two situations discussed above become two special cases now: if the arcs are weighted zero, then essentially it means U-turns are cost-free; if the arcs are weighted infinity, then essentially it means U-turns are banned.

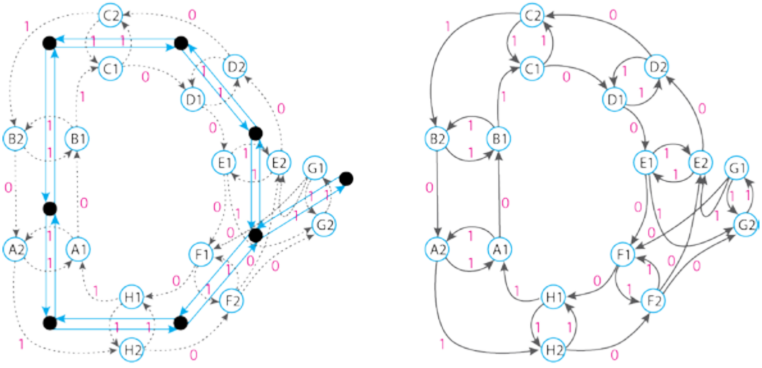
Since we assume the movement on A is bidirectional, to capture the possibility of heading from A in both directions, we run Dijkstra's algorithm twice, with A1 and A2 as the source node respectively. For example, to find the shortest directional distance from A to G (with the assumption that the movement on G is also bidirectional), the algorithmic steps are as follows:

1. run Dijkstra's algorithm with A1 as the source node, find the shortest directional distance from G1 and G2 respectively, compare the two values and temporarily store the smaller one—a shorthand for this step could be *min(dist(A1, G1), dist(A1, G2))*;
2. run Dijkstra's algorithm with A2 as the source node, find the shortest directional distance from G1 and G2 respectively, compare the two values and temporarily store the smaller one—a shorthand for this step could be *min(dist(A2, G1), dist(A2, G2))*;
3. compare the temporarily stored results yielded from the two runs, and save the smaller one as the true shortest directional distance from A to G—a shorthand for this step could be *min(min(dist(A1, G1), dist(A1, G2)), min(dist(A2, G1), dist(A2, G2)))*.



Input street network

Street network with directions indicated



Abstracted to a weighted directed graph

Graph representation of the original network

Figure 2 - Modified graph representation of the original street network for the directional reach analysis. Here the edge weight indicates the directional distance between two nodes.

Being capable of explicitly control the cost of taking U-turns, our algorithm can also be readily applied to a complex street network model where certain directions of traffic are restricted along the streets. In fact, it would only be a matter of editing the graph representation so that it reflects the restrictions on certain movement directions along the streets, without the need to change the core of the algorithm. Despite the potential benefits we mentioned above, we are aware of an obvious downside of the algorithm which is associated with the significant increase in the number of edges as compared to the undirected graph. It could be an issue if one is particularly concerned about the computational speed for running reach analysis on large street networks.

4. CAVEATS

In this section, we illustrate a few scenarios that require special attention when using the Grasshopper Reach Analysis Toolkit. Before we go into those issues, we first discuss the motivation behind choosing the line segment instead of the road segment as the basic unit of reach analysis.

4.1 LINE SEGMENT AS THE BASIC UNIT OF REACH ANALYSIS

Using the line segment is sometimes preferable to using the road segment as the basic unit of reach analysis—especially when the road segment is configurationally differentiated along its entire length.

Take the road segment AB in Figure 3 for example. Suppose that we are running the linear-reach analysis (i.e., the zero-direction-change-reach analysis) for AB and suppose that the angle threshold that we use to count as a direction change is relatively small so that traversing through the zigzag involves a series of sharp turns. Then we choose the midpoint of the road segment to be the starting point (as marked by the pink circle on the line segment cd) and see how much street length is accessible from that point without involving any direction changes. In this case, because one cannot go further beyond the endpoints of the line segment cd without taking turns, the linear reach of the road segment AB from its midpoint is essentially the length of cd. The linear reach value for AB that is calculated as such, however, would misrepresent the nature of the left portion of AB, which is a relatively long and straight line segment. Hence using the line segment as the basic unit of reach analysis here would be more appropriate.

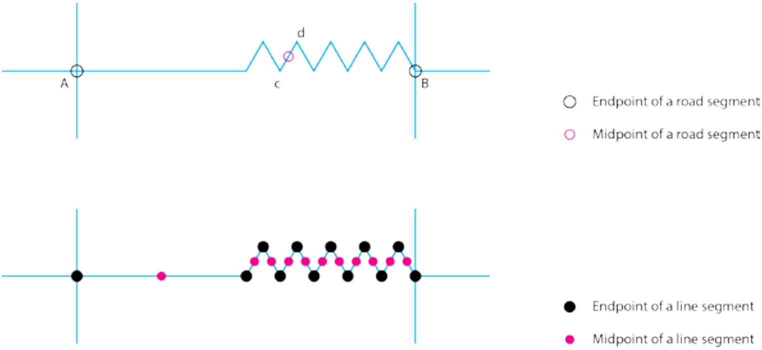


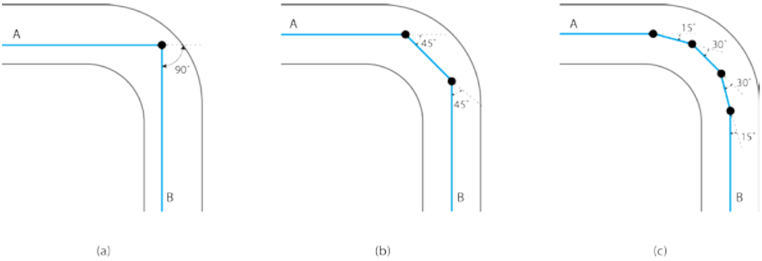
Figure 3 - Illustration of the difference between the road segment and the line segment.

We also notice that if the input street map was originally drawn with a CAD or GIS program, processing it into line segments usually involves less effort than processing it into road segments where special care is needed to ensure that the lines are joined properly between the street intersections.

4.2 TWO REALITIES

The issues that we bring up here have nothing to do with the soundness of the algorithms that we have designed for our toolkit. Instead, they are related to the quality of the input data of the street network and related to the theoretical question of how we should model and represent the spatial structure of our cities. Those issues essentially represent the conflict of two different realities—one reality regards the geometric shape of the road, while the other regards how people perceive and understand the structure of the street network. Here, we are more interested in bringing these issues to the table for a broader discussion than providing definite solutions.

One common issue is about how to model a road curve with line segments. In Figure 4, we illustrate different ways of modelling a sharp turn in the street, with increasingly higher fidelity to the geometry of the curve from left to right. If we consider a deviation angle that is greater than 30° as a direction change, then in Figure 4(a), it would take one turn to get from A to B; in Figure 4(b), it would take two turns; and in Figure 4(c), because none of the angles is greater than 30°, there would appear to be no turns! Although Figure 4(c), among the three, is the best approximation to the reality of the shape of the road, a directional reach analysis based on this representation may not reflect the reality of how a human being normally perceives and understands such a space.



(a) (b) (c)

Figure 4 - Different ways of modelling a road curve.

In fact, the above observation also speaks of the "very-short-line-segments" problem mentioned by Peponis et al. (2008, p. 893)—that is, if very short lines are used, even a relatively sharp turn can resolve itself into a great number of smaller angles of deviation that might pass the test of a reasonably small threshold angle used to count as a direction change. As an expedient solution, they suggested to start accumulating the angle of direction change when the analysis encounters two or more consecutive line segments whose length is below a given metric threshold (Peponis et al., 2008, p. 893). We, however, did not implement this strategy in the current version of Grasshopper Reach Analysis Toolkit. We preferred to relay this issue to the users so that they can deliberately model the input street network in the way that suits best their purpose of analysis.

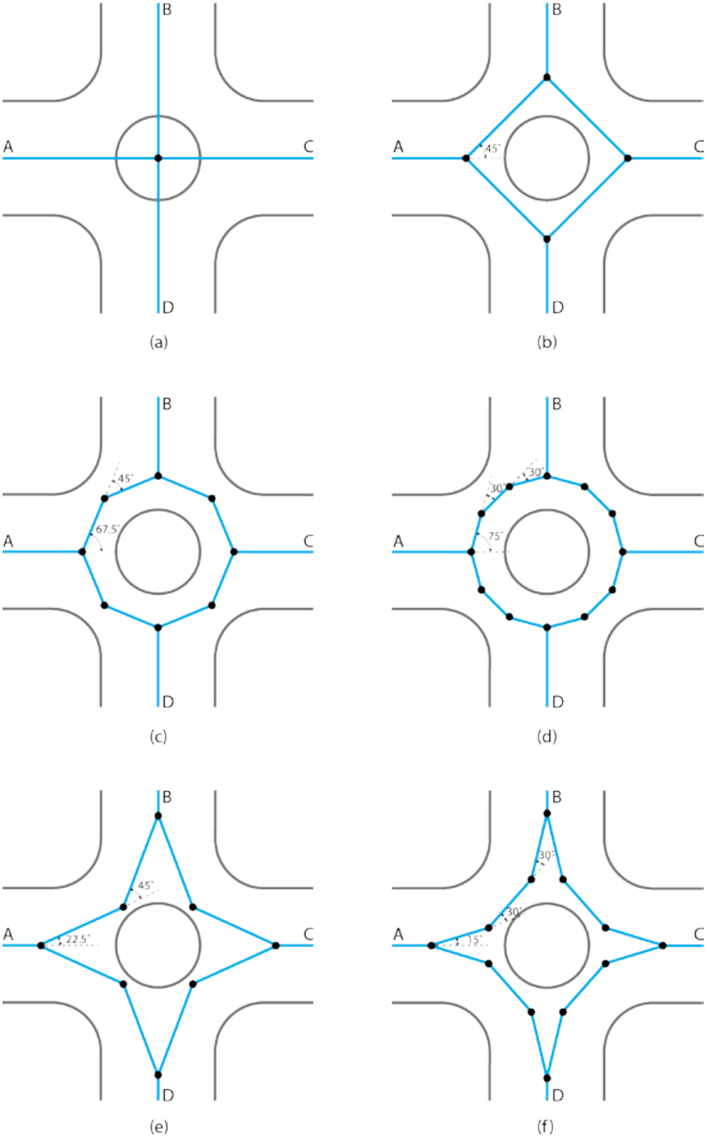


Figure 5 - Different ways of modelling the roundabout at a street intersection.

A related but more complex issue is about modelling the roundabout at a street intersection. Figure 5 illustrates a number of different ways of modelling the roundabout at a cross intersection. Suppose that we only count as a direction change if the angle of deviation is greater than 30° and here we are interested in the directional distance from A to B, C, and D, respectively. It is clear that different representations of the roundabout will yield dramatically different results: in Figure 5(b), it would take two turns to travel from A to either B or D, and an additional turn to get to C; in Figure 5(d), it would always take two turns to get to B, C, and D, and likewise it would take two turns to go through the roundabout and travel back to A itself—which is quite different from the representation in Figure 5(b) based on which it would take 5 turns to get back to A through the roundabout; in Figure 5(f), because the line segments closely follow the curves of the streets bounding the adjacent blocks instead of the roundabout, it would take no turns to travel from A to B and D, and only one turn to get from A to C. Figure 5(a) illustrates the simplest way to model such an intersection and defies the existent geometry of the roundabout. However, one might find that this representation indeed more accurately reflects the reality of people's perception or understanding of this space. Of course, a more complex modelling technique is needed if we would like to show further the real flow of traffic—a third reality.

The third issue occurs when modelling a cross intersection where the centrelines of the incoming streets are not perfectly aligned and do not converge at a single point. As shown in Figure 6(a), the centrelines of the two vertical streets hit the centreline of the horizontal street at two points that are only slightly apart. Nevertheless, based on the algorithm we presented, it would be registered as two turns as one travel from one of the vertical streets to the other because, in principle, one needs to take a turn to travel a distance along the horizontal street—no matter how small that distance is—then take another turn to get to the street on the other side. Since it is very unlikely for a pedestrian to perform the two turns to cross the horizontal street and even less likely to mentally register the two turns, we suggest editing the centrelines of the vertical streets so that they do converge at one point, as illustrated in Figure 6.

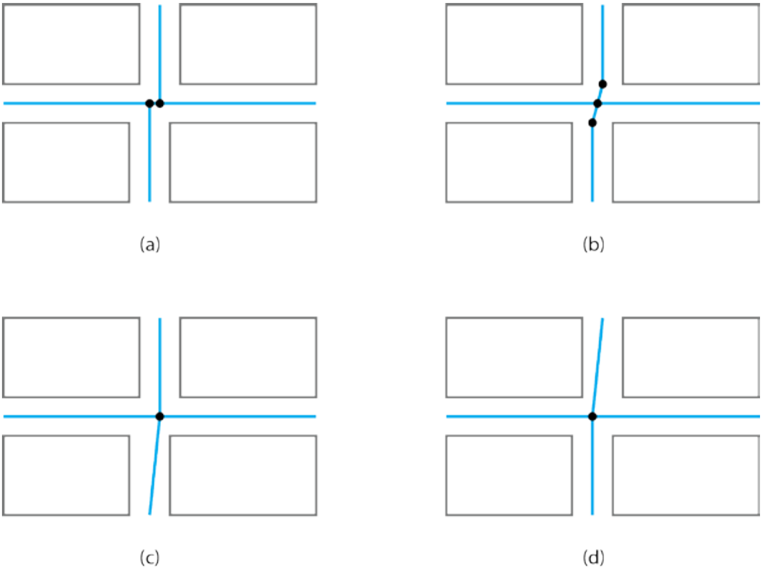


Figure 6 - Different ways of modelling a cross intersection where the incoming streets are not perfectly aligned.

5. BASIC FUNCTIONALITIES

The basic functionalities of the Grasshopper Reach Analysis Toolkit are summarized in Table 1.

Single-Source Reach Analysis			
Type of analysis	Input parameters	Output values	Visualization (optional)
metric reach	• line ID (i.e., the source) by typing or interactive selection • distance threshold	metric reach value for the selected line	• line ID tags • midpoint of the source • lines and fractions of lines within reach
directional reach & DDL	• line ID (i.e., the source) by typing or interactive selection • angle threshold • max number of direction changes	• directional reach value for the selected line • DDL value for the selected line	• line ID tags • midpoint of the source • lines within reach
Multiple-Source Reach Analysis			
directional reach	• line IDs (i.e., the sources) by interactive selection • angle threshold • max number of direction changes	• directional reach value for each of the selected lines • aggregated directional reach value	• line ID tags • midpoints of the sources • lines within reach
All-Lines Reach Analysis			
metric reach	distance threshold	metric reach value for each line in the map	lines coloured based on the reach value
directional reach	• angle threshold • max number of direction changes	directional reach value for each line in the map	lines coloured based on the reach value
DDL	angle threshold	DDL value for each line in the map	lines coloured based on the reach value

Table 1 - Basic Functionalities of the Grasshopper Reach Analysis Toolkit

We use the street centrelines of Gassin, a southeastern French commune, as a case study to show the range of reach analyses that could be performed with the Grasshopper Reach Analysis Toolkit in Figure 7.

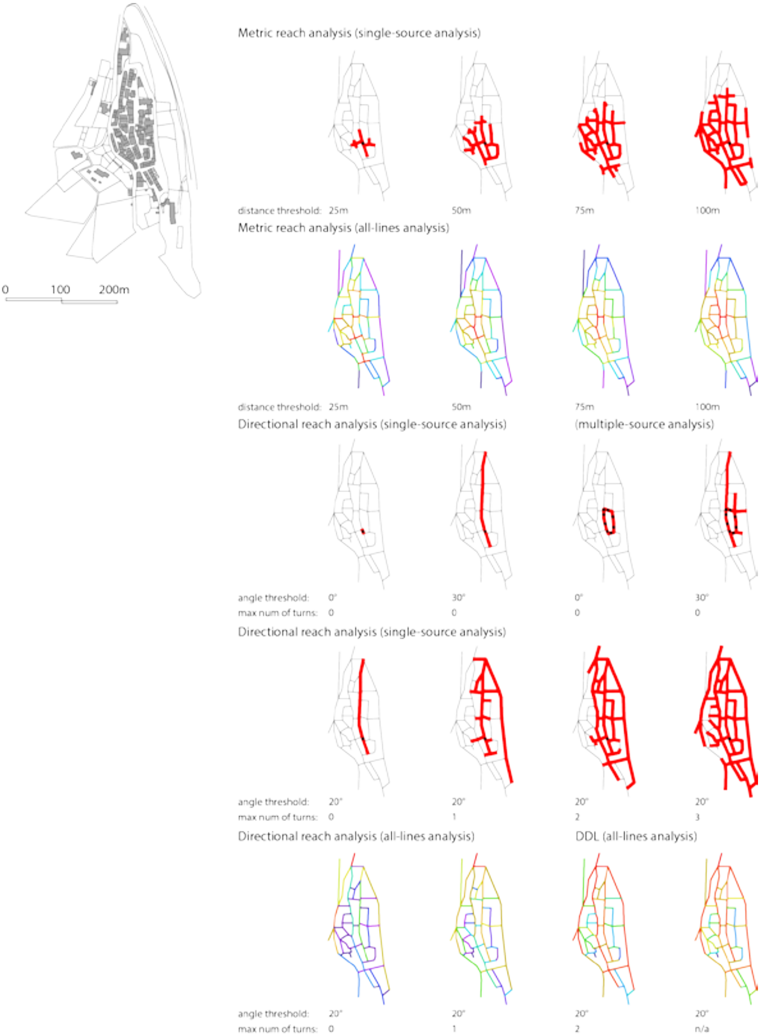


Figure 7 - Reach analysis of the street network of Gassin.

The users can choose different types of reach analysis and, more importantly, can parametrically control the analysis in a straightforward way. Developed as normal Grasshopper definitions, the toolkit is interactive and can be easily integrated with other Grasshopper definitions not only for pure analysis but also for design purposes. One possibility is to treat this toolkit as an analysis component and use it as part of a generative design scheme to arrive at a satisfactory or even the optimal design solution based on certain reach measures.

6. CONCLUSION

We have introduced the basic functionalities of the Grasshopper Reach Analysis Toolkit in this paper. We have also explained the data structure and algorithms that we designed and implemented in developing the toolkit. The motivation behind our work is two-fold: (1) to complement the original version of Spatialist-Lines to enable a smoother dialogue between design exploration and spatial analysis; (2) to open up the potential for integrating the reach analysis as an essential part of the design formulation process by developing the toolkit on a platform that is commonly used for developing computational design tools.

ACKNOWLEDGEMENTS

This work has been funded by Perkins+Will.

We would like to thank Monica Gentili and Matthew Swarts for giving us valuable suggestions about developing the algorithm for the directional reach analysis.

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CAN 3D VISIBILITY CALCULATIONS ALONG A PATH PREDICT THE PERCEIVED DENSITY OF PARTICIPANTS IMMERSED IN A VIRTUAL REALITY ENVIRONMENT?

DAFNA FISHER - GEWIRTZMAN
Technion - IIT, Haifa, Israel
ardafna@tx.technion.ac.il

ABSTRACT

The wellbeing of pedestrians in an urban setting is central concern in the dense urban context for both current and future cities. A sense of crowdedness may greatly influence the public's physical and mental health. Urban centres attract a large concentration of pedestrians and the perception of crowdedness may affect human comfort and even interfere with activity. Structural 3D morphology and additional elements that make up the visible environment, such as vegetation and exposure to a view of the sky influence perception along a pedestrian path. Walking in the centre of a broad boulevard shaded with trees and surrounded by4-6 story buildings would be perceived differently than walking along a side walk adjacent to very tall buildings. Recently, many intense studies have been examining walkability, wayfinding, human cognition and decision-making along pedestrian paths in the urban environment. At the same time, several spatial modelling and analysis tools have been developed to represent and explain variant phenomenon in this complex environment; amongst them models focusing on 3D visual analysis and its relation to human perception. 3D LOS visibility analysis has been found to be an accurate indicator of perceived density experienced by participants in various studies.

In this paper we will present a dynamic LOS 3D visibility analysis for pedestrian paths examining variant layers of visual information including building structure, streets, trees and the afforded view of the sky. A virtual model of the environment was developed using Grasshopper and Rhinoceros software. The model allows for variations of the same path to be examined with several different parameters such as height of buildings, orientation of path, location of path (middle of boulevard or side walk) and the presence or lack of trees. The dynamic movement of walking an urban path was then represented as the accumulated visibility calculations of the viewpoints along that path directed towards a static target point. Model calculations were assessed by way of an extensive experiment in a visualization lab where participants were immersed in virtual reality environments. Participants were asked to imagine they are walking down a main street in a city, towards the end of the street while on their way somewhere. Participants were asked to record their perception of density for each path. The estimate ranged from 1 (not dense at all) to 7 (very dense). The difference in the evaluations between paths was compared to the variance between visibility calculations in the same respective paths. This 3D visibility model may become an essential tool in the planning and design of public spaces in existing and future cities.

KEYWORDS

3D Visibility Analysis, 3D Isovist, Perceived Density in Public Spaces, Urban Environments, Virtual Environment Experiments.

1. INTRODUCTION

The wellbeing of pedestrians in an urban setting is one of the key issues to be concerned about in dense cities (Salingaros, 2005; Borukhov, 1978). A sense of crowdedness may influence the physical and mental health of the public (Berry, 2007). Urban centres attracts large concentrations of pedestrians and the perception of crowdedness may affect human comfort and even interfere with day to day activity. Visual perception has the power to affect people's thoughts and behaviour as the human environment is largely understood through our vision, and visibility influences the perception of space (Cullen, 1971; Broadbent, 1990; Kultsova et al, 2013; Fisher-Gewirtzman, 2016b). In this paper, we refer to the perception of density formed by the morphology of the 3D environment (topography, built structures and large trees) surrounding the observer. Simulating the visibility of urban pedestrians, while walking along urban paths, allows us to get a good sense of their visual perception of that urban space.

Researchers have endeavoured to describe the complexity of the urban structure as well as the analytical models and tools that attempt to represent this complexity while measuring the wide range of data with its numerous characteristics (Batty, 2013). These efforts try to define quality urban environments that provide sustainable and healthy lifestyles. Some academic research, in addition to contributing to science itself, aims at contributing to actual development and improvement of urban planning and urban design practices. The findings are not always accessible to the practitioners in the form of tools or terminologies. Some studies try to overcome this barrier by collaborating with practitioners (Kultsova et al, 2013) or ensure actual consulting, with strategic, evidence-based consulting services.

In this paper we focus on 3D visibility analysis that simulates the way pedestrians would potentially visualize the urban environment while walking along public pathways. The application of our 3D LOS visibility analysis, which in addition to referencing geometry, also takes into account other basic characteristics of the built environment such as the type of surfaces, buildings, pavement surfaces, trees and the view of the distant sky. The ability to distinguish between the different components of the environment and a person's visibility in relation to them, briefly illustrates the great potential for future use of such comparative analysis. To help bridge academic research with practical design, our current 3D LOS analysis tool was developed with Grasshopper and Rhinoceros software, programs that are largely accessible to most architectural or urban design firms.

1.1 OBJECTIVE

The main objective of this study is to develop a 3D LOS visibility analysis for pedestrian movement in urban spaces (such as pedestrian paths and plazas). The model used is based on previous development of 3D visibility analysis (Fisher-Gewirtzman, 2003; Fisher-Gewirtzman, 2006; Fisher-Gewirtzman, 2016).

In this paper we conduct a comparative analysis of the same public path reconstructed with variations of building heights, with and without large trees, different orientations of movement (centre of the boulevard or on the side walk) as well as directions of movement. Our aim was to study how the variations influence the dynamic 3D visibility calculations, simulating the different perceptions.

The final objective presented in this paper was the assessment of the model. Assessment was based on a comparison of the 3D visibility calculations to the participant's evaluation in a virtual reality laboratory. Such controlled studies have been proven to be a reliable source of information (Mavridou, 2012; Portman et al, 2015; Natapov and Fisher-Gewirtzman, 2016). An extensive study in a visualization lab was conducted, where participants were immersed in virtual reality. Participants were asked to imagine they are walking down a main street in a city, on their way somewhere and were asked to record their perception of density for each path. The estimate ranged from 1 (not dense at all) to 7 (very dense).

The assumptions in this study are that 3D visibility calculations along variant paths can be an indicator on the perception of space, while focusing on the perceived density. Prior work confirmed that measured 3D visibility can help predict the perceived density estimation and show how the increased visibility in a space may be evaluated with a lower perceived density (Fisher-Gewirtzman, 2003; Fisher-Gewirtzman, 2015; Fisher-Gewirtzman, 2016a). In some cases, the view rating (Feitelson, 1992; Lang and Schaffer, 2001), or elements in the view such as trees, can overcome limited visibility and influence the perceived density. A conceptual model combining both the quality and quantity evaluation of the view was presented in Fisher-Gewirtzman (2016b) and Golub et al (2017). One of our main assumptions is that 3D LOS visibility calculations simulating visibility in movement will have a strong relation with the participants' evaluations.

1.2 BACKGROUND

A. URBAN DENSITY AND THE PERCEIVED DENSITY

Dense urban environments have become a central issue in recent years, whose impact will only continue to grow in the future. There is a close relationship between density and environmental attractiveness, and an affinity as well as a dependency of urban density on urban environmental quality (Fisher-Gewirtzman, 2006). The question is how to maintain quality dense urban environments and to avoid the feeling of overcrowding.

Perceived density and crowding are based on the principle that the same density can be perceived and evaluated in very different ways by different people, under different circumstances, in different cultures and countries (Churchman, 1999). The concept of perceived density illustrates how physical phenomena can be manipulated in an attempt to increase the probability of either greater or lesser perceived density (Jacobs and Appleyard, 1987). There are several research projects that have investigated the relationship between urban morphology and its experiential qualities perceived by users (Kultsova et al., 2013), and it has been noted that the density of alternative spatial configurations in the same objective density can be perceived differently (Fisher-Gewirtzman et al, 2003; Shach-Pinsley et al, 2006). In this paper, the significance of experienced density refers to the influence the physical 3D environment has on the perceived density, similar to the definition in Jacobs and Appelyard (1987).

Our variant paths share the same urban plan, but represent different physical densities in regard to building's heights: 4-6 stories in height and extremely tall towers. We refer to the visibility and perceived density of the "corridor" created by the towering walls of the surrounding buildings. The variables of our paths include the height of buildings, the existence of large trees and the orientation of pedestrians' path.

B. THE INFLUENCE OF THE BUILT ENVIRONMENT ON PEDESTRIAN BEHAVIOUR AND PERCEPTION

In recent years, many studies have been examining the influence of the built environment on pedestrian behaviour and perception of space (Zacharias, 2001). The analysis at Handy et al (2007) shows that the built environment has an impact on walking behaviour even after accounting for differing attitudes and preferences. Quality walking environments are one of several broad factors influencing walking behaviour, along with demographic characteristics, attitudes and the presence of desirable destinations (Adkins et al, 2012). Based on prior work we argue that low perceived density will contribute to the quality of the pedestrian friendly environment. Forsyth and Southworth (2008) regard scale as an influencing parameter of pedestrian behaviour. They provide a wide range of definitions for walkable environment, all influenced by physical characteristics. Edwing and Handy (2009) suggest operational definitions for human scale as related to the number and length of lines of sight which corresponds with the 3D LOS Visibility Analysis. They argue that the number of long lines of sight contributes to human scale perception as well as other very specific characteristics such as proportions of street level, building heights and vegetation.

Adkin et al (2012) found that green streets, parks, separation from vehicle traffic and pedestrian network connectivity can significantly contribute to walkability. Aligning trees create more pleasant walking paths (Forsyth and Southworth, 2008) and street trees are considered to have the power to moderate the scale of tall buildings and wide streets (Edwing and Handy, 2009; Arnold, 1993), Trees are an important variable in our case studies.

C. VISUAL ANALYSIS AND SIMULATIONS PREDICTING HUMAN PERCEPTION

Visual perception of space is one of the factors that define spatial experience and cognition of architectural or urban space (Kultsova et al, 2013). Lynch (1960) stressed the importance of view analysis using terms such as 'visual absorption', 'visual corridor' or 'visual intrusion'. Many research studies have explored the relationship between urban space morphology and how users perceive their experiential qualities (Fisher-Gewirtzman, 2017) some in 2D and some in 3D visual analysis.

2D visual analysis is based on Isovist measurements, i.e. the 2D field of view from a specific view point, first introduced by Tandy (1967) in landscape geography. Benedikt (1979) introduced the concept to architecture studies, while various visual analysis and tools have subsequently attempted to predict human perception and behaviour. Weiner and Franz (2005) used Isovist measurements to describe indoor scenes, correlating them with behavioural data. They suggested that Isovist measurements are a promising means to predict the experience of space and spatial behavioural tasks.

Space Syntax (Hillier and Hanson, 1984, Hillier, 1996) is a set of analysis technologies that makes use of graphs consisting of paths and nodes aiming at identifying the variables that define the social meaning and behavioural relevance of spaces. This technique was developed to analyse spatial configurations, from room layout to larger urban scale planning, assuming flat topographical conditions. Turner et al (2001) introduced a visibility graph for the spatial analysis of architectural space, and investigates the relationship between the visual characteristics of a location and their potential social interpretation. Batty (2001; 2004) described how a set of Isovist measurements could form a visual field, whose extent defines other Isovist fields of different geometric properties. He suggested a feasible computational scheme for measuring Isovist fields, and illustrated how these could visualize spatial and statistical properties by using maps and frequency distributions. Isovist computation has mainly been used for analysis at building scale, and 'space syntax' is a suitable technique to quantify environmental and spatial indicators at the urban scale.

Dalton and Dalton (2015) give a recent overview of the 3D visibility analysis and representations of three dimensional isovists. They discuss the various attempts and their ability to represent meaningful complex spatial information and invited expert participants to evaluate these various attempts. Their work followed an earlier contribution to 3D analysis by Pen et al (1997), who developed a flexible 3D virtual environment enabling a range of analytics and design support tools including ISOVIST and AXIAL maps within 3D virtual models.

Morelo and Ratti (2009) argued that traditional calculation methods used are too remote from real human visual experience, mainly because the models do not consider the vertical dimension and the dynamic aspect of visibility, namely, moving through space. In Fisher-Gewirtzman and Natapov, (2014) a comparison between 2D and 3D visibility analysis was conducted on an urban site with substantially significant topographic conditions. Rating the calculation outcomes showed that in level areas, both 2D and 3D had similar results but that in sloped areas 2D visibility analysis, did not or could not capture the true nature of the 3D environment.

Wasim S. (2013) developed an algorithm for 3D Isovist measurements, and demonstrated how this model could be integrated with GIS data to influence visibility measurements. Bahtia et al. (2012) made two major contributions to architectural computational analysis, stating that it demonstrated a consistent, 3D Isovist method. Kultsova et al (2013) argued that most visibility analysis methods were not usable and not technically convenient for practitioners and presented a visibility analysis tool for 3D urban environments, and suggested its possible application in urban design practice. Morelo and Ratti (2009) expanded the concept of Isovist i.e. the visible

space from a vantage point in three dimensions, and examined how it could help provide a quantitative basis for Kevin Lynch urban analysis. They argued that their analysis allowed for a more useful interpretation of visibility from a visual perception point of view, because outputs of the analysis are stored in a voxel space. Fisher-Gewirtzman et al, 2013 proposed a similar approach, based on subdividing the virtual urban environment into voxels, which represented a visibility value on a regular grid in 3D space. The model enabled users to compute visibility as a continuous figure with in-between values from fully visible up to fully invisible. The 3D voxel based model was assessed using participants' evaluations to the perceived density.

Subsequently, Fisher-Gewirtzman (2015) developed a LOS 3D visibility analysis tool. This method analysed the sum and segmentation of Lines Of Sight (LOS) at each view point inserted in the virtual built environment. The calculated visibility from each viewpoint is based on the accumulated lengths of lines of sight stemming from each viewpoint representing the visibility from each viewpoint in the direction of observation. The current extension for the LOS 3D method makes it possible to separate various elements in the visible environment, as demonstrated in Fisher-Gewirtzman (2016b). This method was further developed to suit movement along a path and used in the current study that makes a distinction between visibility of buildings and pavements, trees, and the sky in all variant paths.

2. DATASETS AND METHODS

The methodology in this study is made up of three consecutive stages: the first was to develop a 3D visibility analysis model simulating a dynamic experience in an urban setting. The second was to conduct comparative analysis on variations of a possible urban path, where each path demonstrated different parameters that were carefully changed or rearranged. The third and final stage was to assess the model with an experiment conducted in a visualization Lab, where the variant virtual models of the relevant urban path were projected to 75 participants for their evaluations. Following are the descriptions of the first and third stages are explained in details as follows:

2.1 THE 3D VISIBILITY ANALYSIS MODEL SIMULATING A DYNAMIC EXPERIENCE

The purpose of this model is to simulate the visual perception during movement in a built environment i.e. calculate the 3D visibility along a path. The model was based on prior models developed and presented (Fisher-Gewirtzman and Wagner, 2003, Fisher-Gewirtzman et al, 2006; Fisher-Gewirtzman, 2015).

The 3D virtual models were created using Rhinoceros software and calculations were carried out based on code developed in the Grasshopper plugin. Visibility is based on Lines Of Sight from each Viewpoint aimed at a target surface. Calculations sum up the accumulated length of all lines of sight from each viewpoint. The dynamic 3D visibility analysis considers consecutive viewpoints along a path defined by the user. The following steps and images describe the model's features:

Definition of a walking path in the 3D model of the built environment (Rhinoceros), computation to the Grasshopper software as illustrated in figure (1) and creation of a reference point in the walking direction. The user can easily define the maximum length of lines of sight for calculation. Since the model was used as a comparative analysis, the characteristic supporting path length and number of viewpoints were identical: all paths were 800m' in length and 100 viewpoints were evenly spread along all paths.

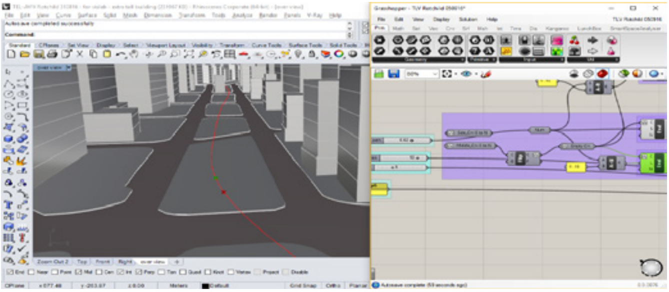


Figure 1 - Defining a walking path in the 3D model

The next step was to create a curved plane representing the 3D field of view, projecting a grid on the plain and drawing lines of sight from the viewpoint, through the grid points towards the surrounding environment as presented in figure (2). The grid points are generated evenly on the curved plain, which represents the field of view in the direction of movement along the defined path. Since a pedestrian can be supposed to have the ability to move his head freely while walking, we referred to a wide potential field of view. The Lines Of Sight (LOS) are intersected by the first opaque element or surface they meet.

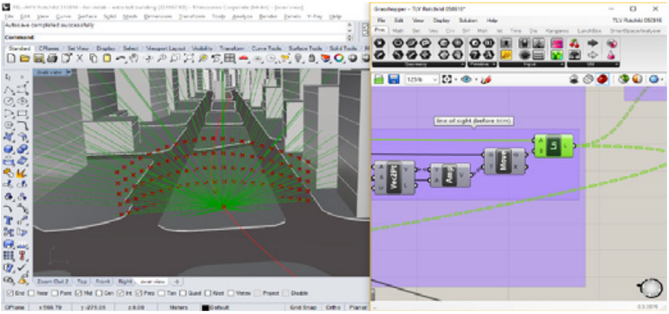


Figure 2 - Defining lines of sight from each viewpoint, through the grid points.

The Lines Of Sight (LOS) are intersected by the first opaque element or surface they meet. The lines of sight can be coloured in accordance to their length as illustrated in figure (3a) (green-long, red-short), or coloured in accordance to the code colour of the layer it reaches (housing, commerce, offices, trees, roads, sky etc.), as illustrated in figure (3b). The colouring by distance represents the LOS distribution and was used to calculate the total visibility for each viewpoint along each path. The colouring by urban function or element was used to calculate separate visibility in accordance to the layer (type of element) the line of sight was intersecting with. This way it was possible to compare how much visibility to building (and building uses) or to trees, water or pavement existed in each path. Additional examples can be found in Fisher-Gewirtzman, 2017a. In this paper, the separate visibility refers to buildings, trees, pavement (street and pedestrian paths) and sky only. The total and separate visibility calculations can be viewed on the right hand-side of table 2.

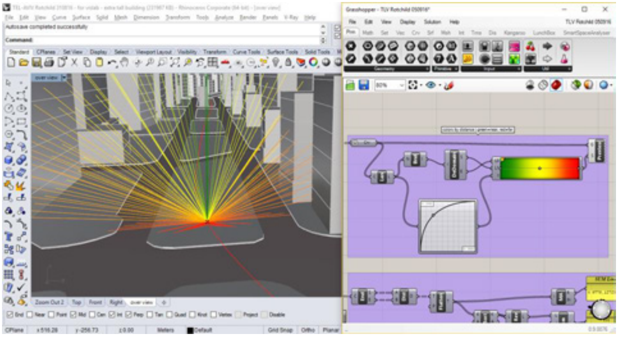


Figure 3a: Lines Of Sight are coloured according to length (red=Short; green=very long)

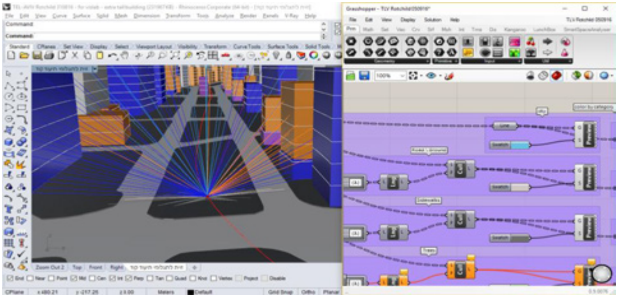


Figure 3b: Lines Of Sight coloured according to the layer (type of element) they intersect.

The final stage consists of summing up the calculations of all viewpoints defined along the path as illustrated in figure (4). The model can provide information regarding the maximum, minimum, average visibility viewpoint along the path, the minimum and average length of LOS (maximum is defined by the user already) visibility distribution to various elements of the environment (defined in layers by the user) etc.

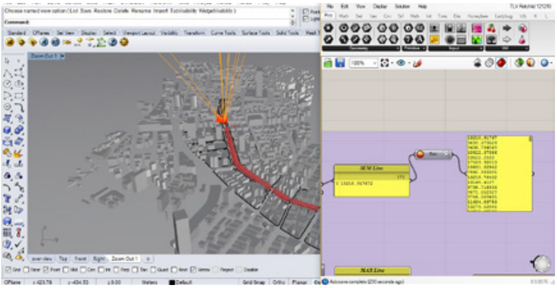


Figure 4: Summing up visibility calculations of all viewpoints defined along the path

The calculation results can be represented by plots that provide a visualization that supports the dynamic characteristics of the simulation and creates a comfortable foundation for comparison.

This model was used to calculate and analyse 3D visibility along variations of the same path. The characteristics of the paths are presented below in table (1). Four longitude sections and perspective views in figure (5) illustrate the variations of the physical environment: existing building heights; existing building heights with trees; additional towers; additional towers with trees. Additional variations are created in accordance to direction of movement and orientation (in the center of the boulevard or walking on the sidewalk. The paths that consist of trees refer to evergreen thick trees that may block visibility. Deciduous trees may bring more variations to the settings of analysis and assessment and are considered for future work.

Group	Path	Contant parameters in groups	variable	variable
A	A-p1	South to North No trees	Center boulevard	Existing buildings
	A-p2		Side walk	Towers
	A-p3		Center boulevard	Towers
	A-p4		Side walk	Existing buildings
B	B-p1	South to North With trees	Side walk	Towers
	B-p2		Center boulevard	Towers
	B-p3		Center boulevard	Existing buildings
	B-p4		Side walk	Existing buildings
C	C-p1	Center boulevard North to South	With trees	Existing buildings
	C-p2		No trees	Towers
	C-p3		No trees	Existing buildings
	C-p4		With trees	Towers
D	D-p1	Towers	North to South	With trees
	D-p2		South to North	No trees
	D-p3		South to North	With trees
	D-p4		North to South	No trees

Table 1 - Group Characteristics

2.2 ASSESSING THE 3D VISIBILITY ANALYSIS MODEL

A controlled experiment was carried out in a visualization lab with 75 recruited participants. The participants varied in profession, in age and in gender. Participants were asked to consider the alternative paths as if they are walking along a central pedestrian street in a city on their way somewhere. They were asked to evaluate their perceived density, ranging from 1 to 7: 1-not dense at all and 7 – very dense. The participants were immersed in virtual reality and exposed systematically to four groups of variant paths. Each group was characterized by some constant characteristics and some variables such as the height of buildings or the existence of trees. The screening order of the paths was shuffled randomly. The paths were presented as short videos, each covering a distance of 80om. Following the experiment, a comparison between the 3D visibility analysis calculation results and the mean value of participant's evaluation for the variant paths presented to them in the lab study was put together for the assessment of the model.

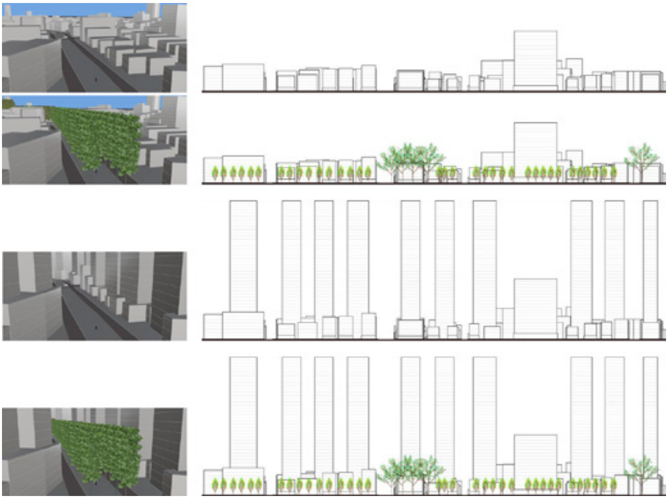


Figure 5: Four longitude sections and perspective views illustrating the variations of the physical environment: (from the top) existing building heights; existing building heights with trees; additional towers; additional towers with trees.

3. RESULTS

In this paper we present three sub-sections for the results:

a. The 3D dynamic (4D) visibility analysis results, b. The Visualization Lab study results and c. Model assessment: a comparison between the lab study results and the 3D visibility analysis results.

3.1 3D DYNAMIC VISIBILITY ANALYSIS RESULTS:

The 3D dynamic (4D?) visibility analysis results are presented in four groups, similar to the groups presented to the participants in the visualization laboratory study. Table (2) presents the paths illustrations and plots demonstrating the visibility calculations along each path. Thirteen different paths were distributed between the four groups. Three of the paths are shared by two groups that were screened to the participants. As such, three of the calculations appear twice. Figure 6 is presenting the separate 3D visibility calculations per each path.

Group A

Path no.	Illustration	Graph	Sum LOS to trees	Sum LOS to built environment	Sum LOS to sky	Total Sum LOS
A1			0.0	388828.8	2861000.0	3249828.8
A2			0.0	661151.2	363000.0	1024151.2
A3			0.0	729385.7	390000.0	1119385.7
A4			0.0	343724.6	2530000.0	2873724.6

Group B

Path no.	Illustration	Graph	Sum LOS to trees	Sum LOS to built environment	Sum LOS to sky	Total Sum LOS
B1			67416.5	424352.0	289000.0	780768.6
B2			67378.3	332486.8	194000.0	593865.0
B3			67378.3	286524.8	838000.0	1191903.1
B4			67416.5	237886.4	1527000.0	1832302.9

Group C

Path no.	Illustration	Graph	Sum LOS to trees	Sum LOS to built environment	Sum LOS to sky	Total Sum LOS
C1			60022.9	280163.8	774000.0	1114186.8
C2			0.0	689012.9	288000.0	977012.9
C3			0.0	391783.1	2576000.0	2967783.1
C4			60022.9	330489.8	134000.0	524512.7

Group D

Path no.	Illustration	Graph	Sum LOS to trees	Sum LOS to built environment	Sum LOS to sky	Total Sum LOS
D1			60022.9	330489.8	134000.0	524512.7
D2			0.0	729385.7	390000.0	1119385.7
D3			28019.5	134725.1	90000.0	252744.6
D4			0	689012.8642	288000	977012.9

Table 2 - Four groups of variant paths and 3D visibility calculations accompanied by graphs for each path.

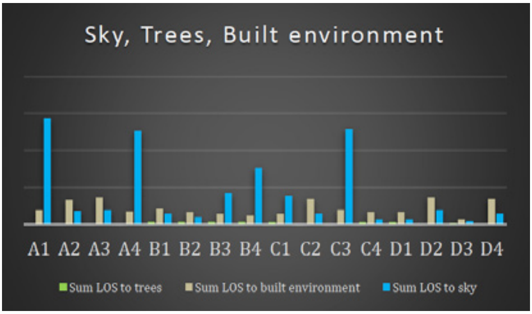


Figure 6 - A representation of the separate 3D visibility calculations per path.

Table (3) shows the ranking of the paths in accordance to their total visibility calculation results. The paths at the top with highest visibility have in common a very open view to the sky. The paths with the lowest visibility at the bottom of the table, all have trees and some are also with very tall buildings that block the openness to the view.

rank	Path no.	Sum LOS Visibility to Trees 10^3m′	Sum LOS Visibility to Built environment 10^3m′	Sum LOS Visibility to Sky 10^3m′	Total 3D Visibility Along the Path 103m′
1	A1	0	388.828	2861	3249.828
2	C3	0	391.783	2576	2967.783
3	A4	0	343.724	2530	2873.724
4	B4	67.461	237.886	1527	1832.302
5	B3	67.378	286.524	838	1191.903
6	A3/D2	0	729.385	390	1119.385
7	C1	60.022	280.163	774	1114.186
8	A2	0	661.151	363	1024.151
9	C2/D4	0	689.612	288	977.612
10	B1	67.416	424.352	289	780.768
11	B2	67.378	332.486	194	593.865
12	C4/D1	60.022	330.489	134	524.512
13	D3	28.019	134.725	90	252.744

Table 3 - Rating of the paths in accordance to their total visibility calculation. Separate calculations are added.

Based on the visibility analysis results we can observe the influence of some of the variables used to manipulate the virtual environments. As an example, let's look at the influence of height by adding towers. Figure (7) presents the total visibility for paths A1 (top) and A3 (below). The only difference between them is the buildings height and as can be expected the visibility is much lower for A3 (with tall buildings). Figure (8) illustrates the separate visibility calculations for the paths. It is observable that the extensive visibility to the sky (blue line) in path A1 is an influencing factor of the visibility calculations.

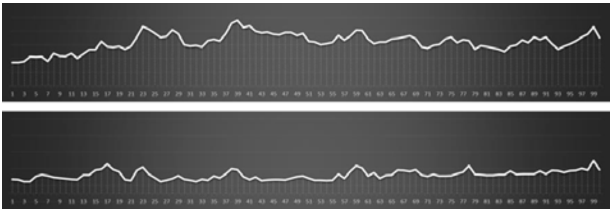


Figure 7 - Total visibility for paths A1 (top graph) and A3 (bottom graph).

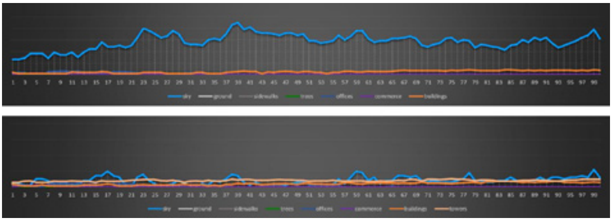


Figure 8 - Separate visibility calculations for paths A1 (top graph) and A3 (bottom graph).

Another possible comparison can be made between the visibility calculations influenced by the presence of trees. Below is the comparison between path A1 and B3. In both paths the movement is along the center of the boulevard in the same direction with low buildings. In A1 there are no trees and B3-with trees. The 3D calculations results are presented in the graphs in figure (9) (A1-top, B3-bottom). Although the green graph in B3 is very moderate, the trees block extensive visibility to the sky view. The straightforward results show that large trees block the view along boulevard. Does it necessarily have a negative influence on perception? We know from prior studies that it may be exactly the opposite (Lang and Schaffer, 2001, Fisher-Gewirtzman, 2016a). Visibility calculations take into account the geometry alone. We can only assume the impact of other elements that make up the view, on perception. This will be examined in a later section that compares visibility calculations with the participant's evaluations.

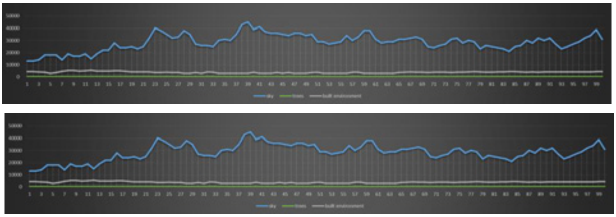
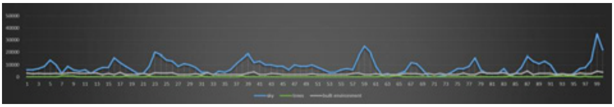
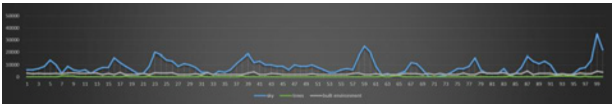


Figure 9 - Comparison of the 3D visibility results between paths A1 and B3.

Another comparison can be made between D3 and D4. In both paths, the movement is along the centre of the boulevard and with very tall buildings. In D3 there are trees along the centre of the boulevard while in D4 none are present. As can be observed in the graphs in figure (10), the visibility calculations are much lower for D3. Again, this is a result of the trees blocking the visibility to the sky, similar to the comparison between A1 and B3 with the low buildings. Visibility without the trees is almost 4 times higher than with the trees in this comparison.



D-3 3D visibility calculations=252.744*10^3m’



D4 3D visibility calculations=977.612*10^3m’

Figure 10 - A comparison between the graphs representing the 3D visibility calculations of path D3 and D4.

3.2 VISUALIZATION LAB STUDY RESULTS:

In this paper we present the ranking of the participants’ evaluation to their perceived density in a mean value for each of the paths and cross-reference those calculations with the main conclusions from the lab study. Table (4) presents the mean value of the participant’s evaluations for all paths in accordance to their groups (A, B, C, and D).

rank	Path no.	Perceived density mean
1	A1	2.28
2	C3	2.65
3	A4	3.04
4	B4	3.21
5	B3	3.25
6	C1	3.60
7	C2	4.05
8	D2	4.20
9	D4	4.29
10	B2	4.40
11	D1	4.41
12	D3	4.43
13	C4	4.48
14	A3	4.53
15	B1	4.56
16	A2	4.99

Table 4 - Ranking of variant paths in accordance to the mean value of the participant’s evaluations. (1-not dense at all; 7-very dense)

A1 and C3 are very similar. In both paths movement is taking place in the centre of the boulevard, with no trees and low buildings but they differ in their direction. Therefore, the visibility calculations are both very high and participant's evaluation indicate the lowest perceived density. In a previous study (Fisher-Gewirtzman, 2017) where the results of the virtual reality study in the visualization lab were carefully analysed, various insights stand out:

Regarding the presence of trees: While walking in the centre of the boulevard with existing buildings, the trees increased the perception of density significantly (as seen in path B-3) but while walking on the sidewalk with additional tall buildings, the trees significantly decreased the perception of density (like in B-1). Regarding orientation: Paths without trees were perceived as much denser while walking on the sidewalk and significantly less dense while walking in the centre of the boulevard.

Regarding height of buildings: Tall buildings increased the perception of density significantly, but to a different degree depending on the presence of trees (perceived as less dense) and the direction of movement. In the next section we will look for the relation between the 3D visibility calculations and the participant's evaluations.

3.3 ASSESSMENT RESULTS:

The assessment of the 3D dynamic visibility model was based on several comparisons between the results of both stages. All paths were ranked in accordance to both total visibility calculations and mean value of the participant's evaluations. In table (5) both assessments appear side by side. It is interesting to note that the first five paths are ranked identically in both. The paths with the largest extent of visibility were ranked with the lowest perceived density by participants and in the same descending order. This confirms the strong correlation between visibility and perceived density in the case of high visibility. Additionally, several paths were ranked with a recognizable similarity by both: C1 was ranked 8th by 3D visibility calculations and 6th by the overall participants' evaluation. D4 was ranked 10/11 by 3D visibility calculations and 9th by the

Rank (visibility calculations)	Path no.	Total 3D Visibility Along the path 10^3m′	Rank (participants Evaluations)	Path no.	Perceived density Mean value
1	A1	3249.828	1	A1	2.28
2	C3	2967.783	2	C3	2.65
3	A4	2873.724	3	A4	3.04
4	B4	1832.302	4	B4	3.21
5	B3	1191.903	5	B3	3.25
6/7	A3/D2	1119.385	6	C1	3.60
			7	C2	4.05
8	C1	1114.186	8	D2	4.20
9	A2	1024.151	9	D4	4.29
10/11	C2/D4	977.612	10	B2	4.40
			11	D1	4.41
12	B1	780.768	12	D3	4.43
13	B2	593.865	13	C4	4.48
14/15	C4/D1	524.512	14	A3	4.53
			15	B1	4.56
16	D3	252.744	16	A2	4.99

Table 5 - ranking the 3D visibility calculations and overall value of participant's evaluations

overall participant's evaluation. C4 was ranked 14/15 by 3D visibility calculations and 13th by the overall participant's evaluation. In some cases we found pronounced differences in the ranking: A3 was ranked as 6/7 by 3D visibility calculations and was ranked as 14th based on participants evaluations. A2 was ranked as 9th according to 3d visibility calculations but was ranked as 16th and most dense according to participants evaluations. D3 was ranked as 16th, the lowest 3D visibility calculations but 12th by participant's evaluations (as less dense). In the case of low visibility calculations, we noticed that the visible elements and their influence on perception is very noticeable, especially in the case of large trees.

Below, we will examine the paths with the greater differences in ranking that occurred in our comparative evaluation between the 3D visibility calculations and the participant's evaluations:

A3 - A path with extra tall buildings, no trees and walking in the centre of the boulevard. This path was ranked as 6/7 according to the 3D visibility calculations and 14th by participant's evaluations, meaning they perceived this path as very dense. The orientation in the centre of the boulevard afforded good exposure to the sky which in turn led to relatively high visibility calculations even with the presence of tall buildings. At the same time, the geometry probably greatly influenced the perception of the participants. The overwhelming sight of so many tall buildings closing on the person walking in between them may be the reason for the pronounced differences in ranking.

A2 – this path was constructed with extra tall buildings, no trees and allowed for walking along one of the sidewalks. Walking along a sidewalk decreases visibility dramatically and therefore it is not surprising that the 3D visibility calculations are lower than the calculations of path A3 as mentioned above. This rating as the densest path (ranked by participants as 16th) can have two explanations. The first explanation stems from the movement orientation. Walking along the side walk right up next to towering buildings may have greatly decreased visibility but also overwhelmed the participants. The second possible reason may be a technical one. Path A2 was part of a group where all paths had no trees and A2 always appeared right after A1 which was constructed with low buildings and was allowed for walking in the centre of the boulevard. The difference between the two may have been perceived as extreme in this group.

D3 – The entire D group consisted of paths with very tall buildings. The variables include direction, orientation and existence of trees. Movement orientation in path D3 allowed for walking in the centre of the boulevard with trees. Due to the tall buildings and the trees, the visibility calculations are the lowest out of all the paths and it was ranked 16th. On the other hand, according to participant's evaluations it was ranked as 12th. The reason for the divergence no doubt, can be explained by the natural preference for trees along urban paths.

4. CONCLUSIONS

In this study, we developed a 3D visibility analysis described as a dynamic visibility analysis (or 4D visibility analysis) that simulates movement along urban paths. To assess the model we conducted a study that explored the effect of various factors that influenced the perceived density of participants in virtual motion as they walked along variations of a pedestrian path. The same variations were used for the 3D visibility analysis and the comparative ranking of the variant paths. The variations focused on the built elements of the environment including buildings, roads and surfaces, large trees, and the sky. A full correlation was found between the rankings of the 5 paths with the highest visibility calculations where participant's evaluations for the paths perceived then as having a low density. Many of the rest of the paths were very closely rated, and only a few isolated paths received different ratings in both categories. The later, can be explained either based on the experiment or by participants' preferences, such as the preference for large trees along the urban path. Large trees would generally block the afforded view (and this is shown to have a great impact on the visibility calculations), but at the same time, create attractive scenery and contribute to the positive evaluations. Such a model that combines quantitative and qualitative analysis, visibility calculations as well as human preferences would be a stronger predicting tool, as suggested in Fisher-Gewirtzman, (2016).

With the further development of the 4D visibility analysis it may become a tool for the practical use of city planners and designers. This tool has the potential for helping predict the influence of changes being considered in existing urban spaces as well as new projects in developing areas. This study is a contribution to the research and development of future cities and the improvement of public spaces and paths in existing ones for the benefit of pedestrians.

ACKNOWLEDGMENTS

"This research was supported by the ISRAEL SCIENCE FOUNDATION, grant no. 1485/15"

Sincere thanks to Elad Bruchim and Lesli Laufer from the Faculty of Architecture at the Technion for their valuable contribution. They are gratefully acknowledged for their assistance. Gratitude is expressed to the Centre of Urban Science and Progress (CUSP), NYU for hosting the author on her Sabbatical during the writing of this research report.

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#161

USING QUALITATIVE DISTANCE METRICS IN SPACE SYNTAX AND CONFIGURATIONAL ANALYSES

MICHAEL J. FRITH
Department of Security and Crime Science, UCL, London, United Kingdom
michael.frith.09@ucl.ac.uk

ABSTRACT

One interesting result from space syntactic and graph theoretic configurational analyses are their ability to correlate with pedestrian and vehicular movement flows. These analyses function by representing the built environment as a graph of interconnected spaces. Network centrality measures, such as betweenness, closeness and choice, are then applied to quantify each space's role in the network and, in this case, suggest the potential amount of movement. That said, because these three network measures are based on the calculation of shortest routes and attempt to model human movement, they should incorporate how we judge distances. In traditional space syntax distance is measured by the angular change accrued at junctions along a route and elsewhere it is often measured as the physical length of the route. However, and hitherto incorporated in these analyses, given the limitations of human cognition (e.g. Simon 1979), there must be some constraint to the cognitive precision of this spatial information. This idea of cognitive spatial imprecision is not new (e.g. Dutta 1988; see also Montello 2007) and a number of qualitative models have been produced that attempt to describe or emulate human spatial judgements. For example, Montello and Frank (1996) used simulations to test the ability of angular models to emulate real-life angle estimations, including an eight 45° cone model where angles are approximated to the nearest 45°. For qualitative physical distance the research is less developed however, for instance, Hernández et al. (1995) gives examples of metric distances being split into three, four or five categories. Based on this, the present study tests variations of qualitative angular and physical distance metrics by comparing their ability in network analyses to correlate with data on 409 pedestrian and 297 vehicular count observations in central London. The results indicate qualitative metrics can increase the correlation between network measures and movement flows. More specifically, angular qualitative metrics significantly improved a number of correlations between the network measures and pedestrian movement. For example, the eight 45° cone model improved the correlation for angular choice analyses of axial segments from 0.55 to 0.60. However, the tested qualitative metrics rarely or not at all (significantly) improved the correlations between angular analyses and vehicular movement and between metric network analyses and both types of movement. Reasons for these results are discussed with suggestions for future research.

KEYWORDS

Qualitative Metrics, Space Syntax, Graph Theory, Movement Flows, Distance

1. CONFIGURATIONAL ANALYSES AND DISTANCE

One interesting result from space syntactic and graph theoretic configurational analyses are their ability to correlate with pedestrian and vehicular movement flows. Although more comprehensive descriptions can be found elsewhere (e.g. Hillier & Hanson, 1984), these

analyses function by partitioning the built environment into graphs of inter-connected spaces. In traditional space syntax these spaces are defined using axial lines which represent vista spaces and are the fewest and longest hand-drawn straight lines of inter-accessibility passing throughout the urban form (Hillier & Hanson, 1984); or using axial segments where these lines are broken where they intersect other lines (Dalton, 2001; Turner, 2001) and so represent sections of axial lines between two intersections. In other configurational analyses, spaces are derived using street centreline data and in the first case using street segments which are sections of the street network between intersections and/or street end-points. These street segments can also be merged, for example, into named streets (Jiang & Claramunt, 2004) where neighbouring street segments share the same street name and so each space can be described as being semantically distinct. Measures of network centrality, particularly betweenness, closeness and choice (see also Table 1 for definitions and example interpretations of each), are then calculated to quantify each spaces' role within the network and can be used to suggest the potential amounts of movement in each space.

As these three network measures are based on the calculation of the shortest paths through the network, they rely on accurately evaluating distance. That is, since the measures are attempting to model human movement, this distance should relate to cognitive distance and how we comprehend the cost of travel between places (Canter & Tagg, 1975). Originally, space syntax defined this topologically where the distance between spaces is the number of steps (spaces) that must be traversed. For axial line (and somewhat named street) analyses, these steps can be interpreted as changes in direction; as (directly) onward travel is along the same space so no distance is accrued whereas any non (directly) onward travel is to a different space. However, with axial and street segments, onward travel beyond an intersection is to another space so a topological step is always accrued (see also segment problem later). In this case, it is essentially counting the number of intersections. This difference is not trivial as it bifurcates the literature which has focused on the correlation between distance and turnings and generally found encouraging evidence (Bugmann & Coventry, 2005, 2008; Hutcheson & Wedell, 2009; Jansen-Osmann & Berendt, 2002; Sadalla & Magel, 1980). That said, other studies have found mixed (Jansen-Osmann & Wiedenbauer, 2004, 2006) and unfavourable (Briggs, 1973; Herman et al., 1986) results. This can be compared to the studies which consider and find a relationship between distance and the number of intersections (Sadalla & Staplin, 1980b; for an exception see Nasar, 1983; see also Sadalla & Staplin, 1980a).

The validity of topological distance is also questioned due to other wayfinding research. That is, until the late 1990s the long-dominant framework (Montello, 1998) of spatial microgenesis by Siegel and White (1975) posited that spatial knowledge develops in distinct stages including from topological (e.g. knowledge of the topological layout and relationships) to topographical (e.g. knowledge of metric distances and/or relative angular directions). Given this, and that spatial knowledge appears to develop over a year (Evans, 1980) but our primary routes are determined quickly (Rogers 1970, cited in Golledge, 1999), it appeared likely routes are topologically determined. However, as identified by Montello (1998), the idea of longitudinal and sequential spatial knowledge stages is contrary to much research. For example, in relatively recent research (e.g. Brunyé & Taylor, 2008; Foo et al., 2005; Herman et al., 1987; Holding & Holding, 1989; Ishikawa & Montello, 2006; Klatzky et al., 1990; Loomis et al., 1993; Montello & Pick Jr, 1993; Ruddle et al., 2011) it is shown that we can synthesise topographic information relatively instantaneously and this can be concurrent with or before acquiring topological knowledge. As such, models of human wayfinding should incorporate topographic detail.

Although largely independent to the above research, and in fact partly proposed to overcome the segment problem, space syntax introduced angular distance (Turner, 2000; Dalton, 2001; Turner, 2001). Here, the distance between two spaces is the sum of the angular change at intersections along the route. In this way it broadly follows from topological distance and the same research except that it recognises that turnings of different magnitudes can be comprehended (Sadalla & Montello, 1989). It also remedies the segment problem where in axial segment and (to some degree) street segment topological analyses where a linear space is broken into its constituent segments, there is a step cost between each discretised segment.

That is despite those segments being linearly-connected and no true turning being made. In contrast, using angular distance, linearly-connected segments cost nothing to transfer between as the deviation angle is 0° and approximately linearly-segments cost proportional to the change in angle (see also Turner, 2001, 2007).

Although less commonly used and arguably underutilised in configurational analyses (Montello, 2007), distance can also be defined metrically where the distance between two spaces is the physical length of the route. While studies suggest features such as turns (see earlier) can distort the relationship between the actual metric distance and the cognitive distance and that this relationship may be linear (Cadwallader, 1973; Day, 1976; Howard et al., 1973), non-linear (Briggs, 1973; Sherman et al., 1979) or either (Canter & Tagg, 1975; Wiest & Bell, 1985); they are often strongly correlated with coefficients above 0.80 (MacEachren, 1980) and 0.90 (Cadwallader, 1973; Canter & Tagg, 1975; Howard et al., 1973).

Network centrality measure	Mathematical definition	Example interpretation
Betweenness	The number of shortest paths between all spaces that pass through the focal space.	The through-movement potential of a space or how likely a space is to be visited on trips through the network.
Closeness	The inverse of the mean shortest distances from the focal space to all other spaces.	The to-movement potential of a space or how easy a space is to navigate to from all other spaces.
Choice (Normalised Angular Choice)	The betweenness of the focal space divided by its distance from all other spaces	The combination of the through- and to-movement potential of a space or how likely a space is to be visited on trips through the network normalised for how easy it is to navigate to.

Table 1 - Mathematical definitions and example interpretations of the three main network centrality measures used for correlating with movement flows

Sources: Freeman (1977; 1979); Hillier (2005); Hillier et al. (2007).

Support for metric distance can also be found in other research that corroborates turns-based distance as regardless of the number of turns, longer paths are (still correctly) often recalled as longer than the shorter paths (e.g. Hutcheson & Wedell, 2009; Jansen-Osmann & Wiedenbauer, 2006).

2. QUALITATIVE DISTANCE

All this being said, given the limited capacity of human cognition in terms of sensing, encoding, storing into memory and retrieving and recoding from memory (e.g. see Simon, 1979), there must be some constraint to the precision of spatial information that is comprehended. This is especially likely for topographical information (such as angles or distance) as it is infinitely precise. For example, consider Figure 1 and the axial line map in 1a; and the same map with all lines removed that do not contribute to the plausible shortest paths between 'Buckingham Palace' (A) and 'Downing Street' (I) in 1b. Is the angular change in the turning from F to H (95°) discernibly greater to that from H to I (92°)? Or is the length of the segment from the intersection of D-F to F-H (276m) discernibly greater to that from F-H to H-I (240m)? Also, is the route from A to I via B, E and G (which is 386° and 1.7km long) discernibly shorter or longer than the route via C, D, F and H (which is 376° and 1.4km long)?

This idea of cognitive spatial imprecision is not new (e.g. Dutta, 1988). Nor has it yet been proposed for space syntax and similar analyses (Montello, 2007). In terms of the cognitive discernibility of angles at-least, methods to incorporate this using qualitative representations of

distances are reasonably well developed (Montello & Frank, 1996). In qualitative representations of distance, also called qualitative distance metrics, distance is measured using qualitative ordinal classes (see below) whereas in the standard approach, which can be called quantitative representations of distance, distance is measured on an absolute ratio scale (e.g. the number of metres or degree of angular change). For example, based on experiments in Sadalla and Montello (1989) where participants estimated the angle sizes of turns they walked, Montello and Frank (1996) used computer simulations to evaluate two models of human angle estimations: a 4-cone model where angles are approximated to the nearest 90° and an 8-cone model where they are approximated to the nearest 45° (see also Figure 2c and 2d respectively). Though these models lacked a strong theoretical a priori, and the cone boundaries may idiosyncratically and aggregately differ (e.g. Franklin & Tversky, 1990; Klippel & Montello, 2007), the results nonetheless highlighted their viability as models of spatial angular perception.

In comparison, there has been less research on qualitative models of metric distance. Frank (1991) briefly suggests distance could be modelled with two (near and far) or three (near, intermediate and far) categories. Fisher and Orf (1991) considered the former of these with distances around a university campus but found the categories were interpreted idiosyncratically. Whilst Hernández et al. (1995) gave the examples of three (close, medium and far), four (very close, close, far and very far) and five (very close, close, commensurate, far and very far) categories. Whilst not explicitly explored in these studies, one issue for metric distance models is whether the total journey length that should be categorised or each segments' length. Here, and notwithstanding the lack of direct empirical evidence, the latter is tentatively suggested as a number of studies (Allen, 1981; Allen & Kirasic, 1985; see also Berendo & Jansen-Osmann, 1997) identify the role of intermediary segments and a relationship between route segmentation and route length estimates.

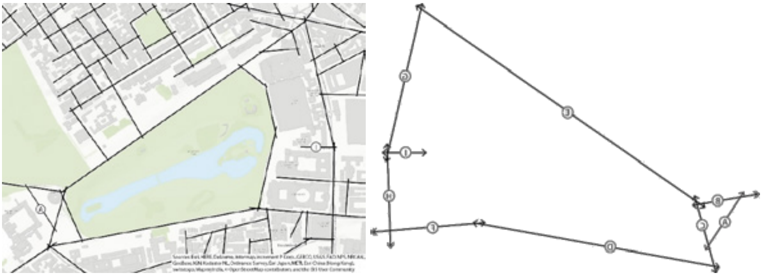

Figure 1 - Axial line maps showing the street network between 'Buckingham Palace' (A) and 'Downing Street' (I) (1a); and with all lines that are extraneous for calculating the plausible shortest path(s) (using angular and metric impedances) between these landmarks removed (1b)

3. THIS STUDY

Based on this research, this study proposes to extend the space syntactic and graph theoretic literature by testing qualitative topographical (angular and metric) distance models. That is, by comparing network measures using quantitative (the approach hitherto in these analyses) and qualitative angular and metric distances in their ability to correlate with pedestrian and vehicular movement flows. This will be conducted by taking angular and metric distances and categorising them into homogenously-sized classes which differ in size for each model. That is where the size of the class relates to the level of precision that turnings are perceived. As shown in Figure 2 for an individual facing the dashed line, for angular distance these include

cone sizes of 15° (a 13-way directional change model); 30° (a 7-way directional change model), 45° (a 5-way directional change model) and 90° (a 3-way directional change model)[1]. From this, in terms of the qualitative angular models it is expected:

> ***Hypothesis 1:*** The correlation between network measures and movement will be significantly stronger in angular analyses using qualitative distance than quantitative distance.

Also, although the intention is to test the 3-way and 5-way angular models from Montello and Frank (1996), the 7-way and 13-way models are included for comparison and it is expected:

> ***Hypothesis 2:*** The correlation between network measures and movement will be significantly stronger in angular analyses using 5-way and 3-way qualitative distance models than the 13-way and 7-way distance models.

Based on the results in Montello and Frank (1996) (see earlier), it is also expected:

> ***Hypothesis 3:*** The correlation between network measures and movement will be significantly stronger in angular analyses using 5-way qualitative distance models than 3-way distance models.

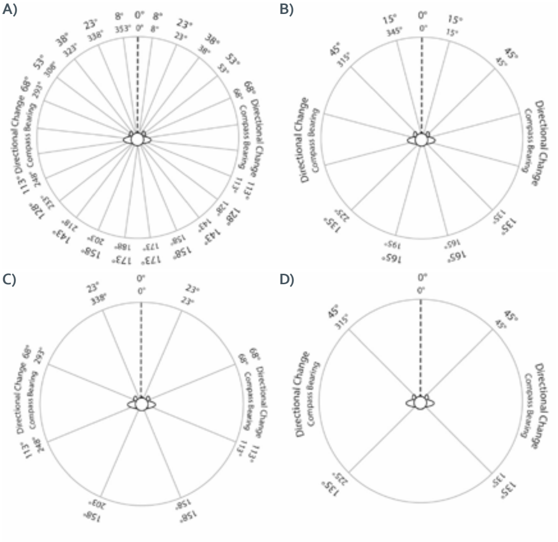

Figure 2 - The 15°-class 13-way (a), 30°-class 7-way (b), 45°-class 5-way (c) and 90°-class 3-way (d) qualitative angular models

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[1] It is worth noting that unlike the analyses in Montello and Frank (1996), configurational analyses only consider absolute directional changes and so do not distinguish between left and right turnings. For example, the 3-way directional change model (as described in this paper) has directional change classes of 0°-45°, 45°-135°, 135-180° (see also Figure 2D). In comparison, in Montello and Frank (1996) the same model would be described as a 4 90° cone size model (where the cones are 315° - 45°, 45°-135°, 135°-225° and 225°-315°). In this way, the models tested in these analyses are equivalent to those described in Montello and Frank (1996) as 24 cone (the 13-way model), 12 cone (the 7-way model), 8 cone (the 5-way model) and 4 cone (the 3-way model) models.

For metric distance, and in lieu of strong a priori knowledge, four models with class sizes with intervals of 25m, 50m, 100m and 250m are tentatively tested. Here it is anticipated that:

Hypothesis 4: The correlation between network measures and movement will be significantly stronger in the metric analyses that use qualitative distance than quantitative distance.

Furthermore, although no hypotheses are explicitly made it is tentatively anticipated that the qualitative metric models with the largest intervals (e.g. 250m) and the smallest intervals (e.g. 25m) will yield weaker correlation coefficients than the other models (those with 50m and 100m intervals). This is reasoned because these models are likely to represent distance judgements too coarsely or too finely respectively.

4. METHODOLOGY

To test these models and their ability to correlate with movement flows, 409 pedestrian and 297 vehicular count observations in central London are taken from two datasets. The first dataset, as originally used in Penn et al. (1998), includes 312 pedestrian and 233 vehicular count observations from Barnsbury, Clerkenwell and Kensington. The second, as used in Penn et al. (1998; see also Chang & Penn, 1997, 1998), includes 98 pedestrian and 64 vehicular count observations from South Bank. Note that the first dataset, as provided, is missing 58 observations which are omitted for various reasons (Iida, 2006) whilst a further nine pedestrian and two vehicular observations are omitted because they could not be georeferenced for all street network representations. From the second dataset, 10 pedestrian and three vehicular observations are also omitted because they could not be georeferenced for all street network representations. These data regard the average number of 'moving adults' or 'moving vehicles' observed in each space per hour.

Pedestrian and vehicular graphs for each of the street network representations described earlier (street segment, named street, axial line and axial segment) were generated from Ordnance Survey network data. This includes where the axial line (and axial segment) graphs were hand-drawn following the space syntax methodology (for example see Al-Sayed et al., 2014). Each graph is then analysed using the common graph theoretic measures of betweenness and closeness and the space syntax measure, (normalised angular) choice[2] (see also Table 1). Based on similar use within the literature and the results from a meta-analysis (Frith et al., 2016) these measures are calculated using radii (to ignore distant spaces that should have no influence on the properties of each space from the measure calculations) of 2000m for the pedestrian analyses and 5000m for the vehicular analyses. These were all computed using a program written in Python by the authors of this paper.

Unlike similar analyses in this literature, the Kendall Tau-a rank correlation coefficient (τ) is used to quantify the correlation between these data. This is because in most studies it is found there is a non-linear relationship between these variables. As such, to use the popular Pearson's r correlation coefficient would require one of any number of data transformations. In comparison, the τ statistic only considers the relative ranks of the data and because those data transformations do not change the order of the data, they are redundant as they will not affect the correlation. The τ coefficient can be interpreted as the probability that for any two pairs of metric (X) and observation (Y) data that $X_j - X_i$ and $Y_j - Y_i$ are concordant and share the same or opposite signs. The values range from -1 if all combinations of pairs possess different signs (i.e. there is a negative relationship), 0 if there is perfect discordance and each sign is equally likely and 1 if they all possess the same sign (i.e. there is a positive relationship). That said, because τ coefficients appear smaller in magnitude compared to other indices such as Pearson's r, Greiner's relation is used to calculate and show the approximate equivalent r values (Kendall, 1949).

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[2] Note that as briefly alluded to the possibility of in Hillier et al. (2007), the betweenness-choice normalisation procedure used to calculate (normalised angular) choice - typically used for angular analyses of axial segment - is also used to create choice measures for angular analyses of networks built from the other units (axial lines, street segments and named streets) and for metric analyses of all four types of networks.

The correlation coefficients are computed using the somersd package (Newson, 2014) in Stata (StataCorp, 2015). To test the hypotheses, the correlation coefficients are compared using Wald tests (using the lincom command also in Stata) which determine if they differ significantly (i.e. that one model is a better estimator of movement and so has a higher correlation coefficient than the other model). Also, because multiple comparisons are necessary for some hypothesis, for example in hypothesis 1 where four qualitative angular models are compared to the quantitative angular model, multiplicity and the increased likelihood of incorrectly rejecting the null hypothesis is controlled using the Bonferroni correction.

5. RESULTS

For parsimony, Tables 2 and 3 summarise the results and show the estimated correlation coefficients between movement flows and angular (Table 2) and metric (Table 3) analyses using quantitative distance and the top correlating equivalent analysis using qualitative distance. The correlation results for all (qualitative distance) analyses can be found in Tables 4-7 in the appendix.

Regarding hypothesis 1, and as shown in Table 2, the results indicate that incorporating qualitative angular metrics in network analyses can increase their correlation with movement flows. In the case of correlating with pedestrian movement, for five of the 12 analyses (combinations of network type and network measure) the correlations were significantly greater when using (at-least one model of) qualitative distance compared to when using quantitative distance. The largest increases are between pedestrian movement and closeness which increases from 0.33 to 0.52 for street segment analyses and from 0.36 to 0.51 for named street analyses; both using the 3-way model. Other notable significant increases include betweenness analyses of axial segments when using the 5–way model (0.53 to 0.57); choice analyses of axial lines when using the 3-way (0.52 to 0.56) and 5-way (0.52 to 0.55) models and choice analyses of axial segments when using the 5-way model (0.55 to 0.60).

Network Measure	Network Type	Pedestrian Movement		Vehicular Movement	
		Quantitative Distance	Qualitative Distance	Quantitative Distance	Qualitative Distance
Betweenness	Axial Line	0.50	0.51†	0.80	0.79
	Axial Segment	0.53	0.57**	0.83	0.81
	Street Segment	0.41	0.37	0.84	0.81
	Named Street	0.34	0.35†	0.82	0.77
Closeness	Axial Line	0.71	0.71†	0.71	0.72†
	Axial Segment	0.66	0.66†	0.68	0.72†
	Street Segment	0.33	0.52**	0.71	0.73†
	Named Street	0.36	0.51**	0.67	0.71*
Choice	Axial Line	0.52	0.56*	0.80	0.80
	Axial Segment	0.55	0.60**	0.83	0.81
	Street Segment	0.40	0.37	0.84	0.82
	Named Street	0.34	0.37†	0.82	0.79

† indicates the qualitative model correlates better but not significantly than the equivalent quantitative model and * and ** indicates the qualitative model correlates significantly better at $p<0.05$ and $p<0.01$ levels respectively.

Table 2 - Correlations between pedestrian and vehicular movement and angular network analyses using quantitative and the top correlating analysis using qualitative distance

In comparison, when correlating with vehicular movement only one analysis correlates significantly more strongly when using qualitative distance rather than quantitative distance. In this analysis, closeness analyses of named streets, the correlation increases from 0.67 to 0.71 with the 7-way qualitative distance model. That said, in a further three (compared to a further five in the pedestrian analyses) analyses, closeness analyses of the other network types, the correlation coefficient increases, but not significantly, when using (at-least one of) the qualitative distance models.

While this compares the angular qualitative models to the equivalent quantitative models, the qualitative models can also be compared to each other to determine which correlate best with movement. For hypothesis 2, in terms of pedestrian movement the correlations for the top correlating 3-way or 5-way model is significantly greater than that for the top correlating 7-way or 13-way model for six analyses (betweenness analyses of axial segments and named streets; closeness analyses of street segments and named streets; and choice analyses of axial segments and named streets). For five analyses (those except closeness analyses of axial lines) the top correlating 3-way or 5-way analysis is still greater but not significantly. In comparison, for vehicular movement the 7-way or 13-way models best correlate in all analyses, including significantly in three analyses (betweenness analyses of street segments; closeness analyses of street segments and choice analyses of street segments).

When comparing just the 3-way and 5-way models for hypothesis 3, the correlations for both types of movement tend to be greater in the 5-way model than the 3-way model. More specifically, the correlation with pedestrian movement using the 5-way model is significantly greater than that with the 3-way model in five analyses (all betweenness analyses and choice analyses of named streets) compared to in two types of analyses for the reverse (closeness analyses of street segments and named streets). For vehicular movement the correlations are significantly greater using the 5-way model of distance for four analyses (betweenness analyses of named streets and closeness analyses of axial lines, axial segments and named streets) while in no analyses is the correlation using the 3-way model significantly than that using the 5-way model.

Network Measure	Network Type	Pedestrian Movement		Vehicular Movement	
		Quantitative Distance	Qualitative Distance	Quantitative Distance	Qualitative Distance
Betweenness	Axial Line	0.45	0.46†	0.71	0.65
	Axial Segment	0.52	0.42	0.77	0.68
	Street Segment	0.34	0.37†	0.80	0.69
	Named Street	0.33	0.34†	0.81	0.63
Closeness	Axial Line	-0.03	-0.11**	0.26	0.19
	Axial Segment	0.01	0.12**	0.40	0.34
	Street Segment	0.05	0.03	0.42	0.33
	Named Street	0.04	-0.04	0.40	0.32
Choice	Axial Line	0.45	0.46†	0.72	0.65
	Axial Segment	0.51	0.41	0.78	0.68
	Street Segment	0.33	0.37†	0.80	0.63
	Named Street	0.31	0.33†	0.81	0.69

† indicates the qualitative model correlates better but not significantly than the equivalent quantitative model and * and ** indicates the qualitative model correlates significantly better at $p<0.05$ and $p<0.01$ levels respectively.

Table 3 - Correlations between pedestrian and vehicular movement and metric network analyses using quantitative and the top correlating analysis using qualitative distance

Regarding hypothesis 4, as shown in Table 3 the results indicate that the qualitative metric distance models do not consistently and significantly increase the correlation with movement compared to the equivalent analyses using quantitative distance. For pedestrian movement two analyses significantly increase in strength when using (at least one model of) qualitative distance compared to when using quantitative distance. These are closeness analyses of axial lines and axial segments which increased from -0.03 to -0.11 and from 0.01 to -0.12 respectively. That said, in six of the remaining 10 types of analyses the correlations increased, but not significantly, when using at-least one model of qualitative distance. These are betweenness and choice analyses of axial lines, street segments and named streets. In comparison, for vehicular movement none of the analyses using qualitative metric distance correlated more strongly (significantly or not significantly) than the equivalent analysis using quantitative distance.

Additionally, and although no explicit hypotheses were made, the correlations for the qualitative metric distance models can also be compared to each other. This includes where it was tentatively expected that the analyses using metric intervals of 50m or 100m would correlate with movement more strongly than those using intervals of 25m or 250m. For pedestrian movement this expectation was supported as the correlation for the top correlating 50m or 100m model was significantly stronger in five of the types of analyses and stronger but not significantly in six of the remaining seven analyses. That said, the results indicate the top correlating models were those with intervals of 25m and 50m, and when these are compared, the analyses using the 50m qualitative distance model correlated more strongly in all analyses except closeness analyses of street segments and this was significant in five of the types of analyses (betweenness analyses of street segments and named streets; closeness analyses of axial segments and choice analyses of street segments and named streets). For vehicular movement the top correlating models were always those using 25m or 50m intervals and when these are compared (which is the same as comparing the top correlating analysis using 25m or 250m intervals to the top correlating analysis using 50m or 100m intervals) the correlations for analyses using 25m intervals were significantly stronger in two analyses (closeness analyses of street segments and named streets) and stronger but not significantly in six of the remaining analyses.

6. DISCUSSION

In this paper novel qualitative models of angular and metric distance were used to test their effect on the ability of network measures to correlate with pedestrian and vehicular movement flows. That is where it was anticipated that network analyses that incorporate qualitative models - and so are likely to better approximate human spatial reasoning - will more strongly correlate with movement than the equivalent non-qualitative (quantitative) analyses. The results from this paper partially support this expectation and indicate that the tested qualitative models of distance can significantly increase the strength of the correlation with movement flows. In other words, qualitative models of distance can improve the ability of network measures to estimate the amount of movement in a space.

More specifically, the results highlighted that when using qualitative angular models of distance, network measures correlated more strongly with pedestrian movement in five of the 12 tested types of analyses. That said, the practical importance of these increases can be examined as the largest increases are found in two of the formerly worst correlating types of analyses (closeness analyses of street segment and named street network representations). Moreover, the overall top correlating model (which uses the 7-way qualitative model of angular distances and closeness analyses of axial lines) does not correlate substantially or significantly more than that of the equivalent quantitative analysis. For qualitative angular analyses of vehicular movement and qualitative metric analyses of pedestrian movement the results are more mixed. In the analyses where the qualitative models correlate more strongly than the equivalent quantitative models, the differences are generally not significant or substantial and the (improved) qualitative-based correlation is notably smaller than that of a quantitative-based correlation for another types of analysis. The tested qualitative models of metric distance did not improve any of the correlations between network measures and vehicular movement.

That said, the possible viability of qualitative models is suggested by the results for hypotheses 2 and 3. That is where the models (used in this paper) found to best emulate real-life angle estimations in Montello and Frank (1996), the 3-way and particularly the 5-way qualitative angular models, tended to correlate more strongly with pedestrian movement than the other qualitative models. Also, and while the 5-way model also correlated with vehicular movement more strongly than the 3-way model, the discrepancy whereby the 7-way and 13-way models overall best correlated with vehicular movement may be explained by the research from which Montello and Frank (1996) is based on, Sadalla and Montello (1989). That is where this research involved participants walking a path and estimating the angular change of direction rather than driving. As such, the qualitative models tested in Montello and Frank (1996) which serve as the basis for those used in this analysis are conceivably calibrated to pedestrian spatial cognition rather than vehicular. This is something future research may consider and particularly if such research considers more sophisticated variants of qualitative metrics such as those also used in Montello and Frank (1996) but were beyond the scope of this paper. Similarly, the mixed results found for the qualitative metric distance models may be somewhat attributable to the general lack of research into this topic whereby the intervals tested in this paper were largely conjectured without strong a priori evidence. This is again something future research may want to consider.

Beyond these issues, it is important to acknowledge other limitations associated with these analyses. The most important limitation is that these results regard one set of analyses using data from just one city. Here, and especially salient as this analysis (of the use of qualitative distant metrics in configurational analyses) is as far as the authors are aware the first of its kind, it is unknown if the results generalise to other locations or even to other data from the same location (London). This issue may also be exacerbated as some of data used in these analyses (the first dataset) were non-randomly missing data-points. For example, six data-points were excluded as they concern cul-de-sacs and therefore do not generate through movement (Iida, 2006). In this way and although these exclusions may have little effect on the correlation results, they may also have substantial effects whereby the results are only generalisable to alike locations. Future research is needed to test this and the replicability of these findings. Given the early stage of this avenue of research, future studies may also want to expand on the types of analyses compared. That is, these analyses only considered limited network centrality measures and representations of the street network. For example, future research may also want to test qualitative distance metrics in more recent analyses including those using alternative network measures such as the PageRank measure (e.g. Jiang, 2006; Jiang, Zhao, & Yin, 2008) or weighted analyses where each space is weighted in the network measure calculations by some measure of its importance or attractiveness as a destination and/or origin (e.g. Karimi, Parham, & Acharya, 2015; Turner, 2007). Lastly, and while the correlation results presented are approximately of the same magnitude as Pearson's values (which are commonly used in similar analyses), it must be reiterated that these are derived from Kendall Tau-a correlation coefficients and should be interpreted as such (including in terms of their benefits over Pearson's correlation coefficients; see earlier).

To summarise, this paper is the first of its kind to test the use of qualitative distance metrics in configurational analyses for their impact on the ability to correlate with pedestrian and vehicular movement. Although the results provide mixed support for qualitative distance metrics, in light of its novelty, future research is suggested to elaborate on these findings and to test other variants of these qualitative metrics.

ACKNOWLEDGEMENTS

This project was funded by EPSRC grant no. EP/G037264/1.

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APPENDIX

Network Measure	Network Type	Quantitative Model	Angular Qualitative Models			
			3-way	5-way	7-way	13-way
Betweenness	Axial Line	0.50	0.48	0.51†	0.50	0.49
	Axial Segment	0.53	0.51	0.57**	0.53†	0.49
	Street Segment	0.41	0.33	0.37	0.35	0.35
	Named Street	0.34	0.26	0.35†	0.31	0.31
Closeness	Axial Line	0.71	0.68	0.69	0.71†	0.69
	Axial Segment	0.66	0.63	0.66†	0.63	0.64
	Street Segment	0.33	0.52**	0.35†	0.33	0.34†
	Named Street	0.36	0.51**	0.41*	0.42**	0.41**
Choice	Axial Line	0.52	0.56*	0.55*	0.54†	0.52†
	Axial Segment	0.55	0.59†	0.60**	0.55†	0.51
	Street Segment	0.40	0.37	0.37	0.35	0.35
	Named Street	0.34	0.33	0.37†	0.32	0.33

† indicates the qualitative model correlates better but not significantly than the equivalent quantitative model and * and ** indicates the qualitative model correlates significantly better at $p<0.05$ and $p<0.01$ levels respectively.

Table 4 - Correlations between pedestrian movement and angular network analyses using quantitative and qualitative distance

Network Measure	Network Type	Quantitative Model	Angular Qualitative Models			
			3-way	5-way	7-way	13-way
Betweenness	Axial Line	0.80	0.76	0.78	0.79	0.79
	Axial Segment	0.83	0.78	0.80	0.81	0.80
	Street Segment	0.84	0.74	0.75	0.77	0.81
	Named Street	0.82	0.73	0.77	0.77	0.76
Closeness	Axial Line	0.71	0.60	0.69	0.71	0.72†
	Axial Segment	0.68	0.61	0.70†	0.72†	0.68†
	Street Segment	0.71	0.64	0.68	0.69	0.73†
	Named Street	0.67	0.60	0.68†	0.71*	0.64
Choice	Axial Line	0.80	0.77	0.78	0.79	0.80
	Axial Segment	0.83	0.77	0.80	0.81	0.80
	Street Segment	0.84	0.77	0.76	0.78	0.82
	Named Street	0.82	0.78	0.78	0.79	0.77

† indicates the qualitative model correlates better but not significantly than the equivalent quantitative model and * and ** indicates the qualitative model correlates significantly better at $p<0.05$ and $p<0.01$ levels respectively.

Table 5 - Correlations between vehicular movement and angular network analyses using quantitative and qualitative distance

Network Measure	Network Type	Quantitative Model	Angular Qualitative Models			
			3-way	5-way	7-way	13-way
Betweenness	Axial Line	0.45	0.41	0.46†	0.37	0.28
	Axial Segment	0.52	0.41	0.42	0.26	0.24
	Street Segment	0.34	0.26	0.37†	0.22	0.11
	Named Street	0.33	0.24	0.34†	0.23	0.16
Closeness	Axial Line	-0.03	-0.07**	-0.11**	-0.06†	-0.07†
	Axial Segment	0.01	-0.06**	-0.12**	-0.06†	-0.07†
	Street Segment	0.05	0.03	0.00	-0.02	0.01
	Named Street	0.04	0.00	0.02	-0.04	0.01
Choice	Axial Line	0.45	0.41	0.46†	0.37	0.28
	Axial Segment	0.51	0.40	0.41	0.25	0.23
	Street Segment	0.33	0.25	0.37†	0.21	0.10
	Named Street	0.31	0.23	0.33†	0.22	0.15

† indicates the qualitative model correlates better but not significantly than the equivalent quantitative model and * and ** indicates the qualitative model correlates significantly better at $p<0.05$ and $p<0.01$ levels respectively.

Table 6 - Correlations between pedestrian movement and metric network analyses using quantitative and qualitative distance

Network Measure	Network Type	Quantitative Model	Angular Qualitative Models			
			3-way	5-way	7-way	13-way
Betweenness	Axial Line	0.71	0.64	0.65	0.57	0.54
	Axial Segment	0.77	0.68	0.65	0.54	0.52
	Street Segment	0.80	0.68	0.69	0.62	0.59
	Named Street	0.81	0.63	0.59	0.51	0.45
Closeness	Axial Line	0.26	0.16	0.19	0.07	0.14
	Axial Segment	0.40	0.34	0.28	0.06	0.13
	Street Segment	0.42	0.33	0.21	0.07	0.24
	Named Street	0.40	0.32	0.17	0.05	0.20
Choice	Axial Line	0.72	0.65	0.65	0.58	0.55
	Axial Segment	0.78	0.68	0.65	0.54	0.52
	Street Segment	0.80	0.63	0.59	0.50	0.45
	Named Street	0.81	0.69	0.68	0.62	0.59

† indicates the qualitative model correlates better but not significantly than the equivalent quantitative model and * and ** indicates the qualitative model correlates significantly better at $p<0.05$ and $p<0.01$ levels respectively.

Table 7 - Correlations between vehicular movement and metric network analyses using quantitative and qualitative distance

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ON AESTHETICS AND SPATIAL CONFIGURATION

DANIEL KOCH
KTH School of Architecture
daniel.koch@arch.kth.se

ABSTRACT

This article takes as its point of departure that any question concerning architecture, in a broad sense, has cultural and aesthetic implications, whether directly concerned with them or focused on social, technical, functional or other concerns. From such an outset, so does spatial configuration. However, while questions of aesthetics have been addressed within syntax research, it has rarely been the central point. This article intends to address more specifically the question of spatial configuration as *aesthetics*, on the one hand, and the *aesthetic implications of configurational analysis* on the other. In doing so, it will discuss aesthetic implications of ostensibly non-aesthetic considerations by addressing aesthetics as cultural, social and formal values embedded in and expressed through architectural works, and mediated through engaged and distracted experience. Concretely, the discussion will revolve around a small selection of works to develop a reasoning around aesthetics and configuration. This includes Alexander Klein's graphic methods to evaluate building plans and its relation to a selection of Mies van der Rohe's works, to conclude with a discussion relating the findings to *habits* and *dispositions*.

KEYWORDS

aesthetics, architecture, morphology, configuration, movement aesthetics

1. INTRODUCTION

My intention in this article is, I believe, rather simple: starting from that architecture is, to a greater or lesser extent depending on definitions, an aesthetic practice, it is reasonable to consider the ways in which spatial configuration forms part of such a practice. Thus, I do not intend to say that all research into configuration should discuss aesthetics, nor that I will present a full theory on the subject. Rather, my position will be that there is need for a more thorough engagement with aesthetics, and that this engagement begins as best not with an attempt to 'prove' that configuration is aesthetics, nor to find empirical support through statistics or observations, but by a discussion that takes its point of departure in a postulation that configuration *is* an aesthetic question, and from such a position investigates *how* it is so and how we can build such a discourse. Such a discussion, I believe, is better engaged with through specifics, engaging with concepts and theories in syntax research but approached from another position.

To be clear 'aesthetics' in this discussion will not concern 'beauty', as do parts of aesthetic discourse (e.g. Pérez-Gómez, 2012; Shelley, 2011; John, 2012). Nor will it concern degrees of impact on sensory experience, or richer or poorer experiential qualities. Instead, I will approach aesthetics from two points of view: as a response to a question such as 'what is the aesthetics of this building' (including structuring and manipulation of experiential qualities), and as experience produced through the interplay between a 'work' and an experiencing audience considered as cultural beings (and thereby conditioned by earlier experiences and expectations; Kaye, 2000).

An important point of origin is how Walter Benjamin discusses aesthetic experience in *The Work of Art in the Age of Mechanical Reproduction* (2008), differentiating two forms of aesthetic experience: that of the art world characterised by the *active engagement of the experiencing subject*, and that of the everyday life of the masses, characterised by a *distracted experience in the everyday*. In a sense, the former can be compared to a common use of Kantian aesthetics (Kant, 1974), and the latter can be linked to pragmatist and everyday aesthetics (Dewey, 1934; Mandoki, 2007). Furthermore, Andrew Ballantyne's (2011) discussion of the role of *habit* in what Benjamin describes as that the masses 'absorb' culture in distracted experiences will be important; i.e. subconscious or unconscious internalisation of values and ideals[1].

Herein lies the core of the proposition of this paper: configurational analysis needs to increase its sensitivity to modes of perception and experience of the environment embedded in the habits of everyday life, and, conversely, that architectural configuration contributes to such embedding in addition to conscious experiential quality or particular effects on use and behaviour. However, the proposition is also that such reflection nuances and develops modes of interpretation of spatial configurations as well as design reasoning. Hereby, it also has implications for how we read and interpret architecture, and what proposals and propositions it makes (Peponis, 2005).

Finally, the position is that giving shape to space and buildings, for whichever ostensible or explicit purpose, on whichever grounds, and following whichever principles, is an aesthetic activity[2]. Here, this is taken in the sense that it by necessity involves deciding priority, choosing preference, and executing judgement over what is given shape and how—but also, how this is arranged and configured, what is hidden, and what is neglected (Foucault, 1986; Koch, 2010). I wish to clarify that with *aesthetics* I mean neither general art theory nor something analogous to 'generative theory' in Hillier's (1996) terms. My position is instead similar to that of Boris Groys in *Going Public* (2010), considering the philosophy of art as consisting of *aesthetsis*, *poesis* and *techne*: experience and evaluation, creativity and exploration, and methods and techniques[3]. However, as is clear in Groys' reasoning, these are aspects of an integrated whole: while I will focus on 'aesthesis', this includes evaluation and consideration in the creative process as well as the imagining coming audiences (e.g. Malm and Wik, 2012). In this sense, I agree with Sophia Psarra (2014) regarding the integrated character of 'generative' and 'analytic' theory: while *aesthesis* is concerned with 'consumption' and 'experience', this does not suggest it is confined strictly to consumers.

2. CONFIGURATIONAL EXPLORATIONS

A key starting point for the coming discussion is architecture as a means by which we "create relatively complex and permanent arrangements of space which function as stable allocentric frameworks for locating ourselves, other people, and things as we go about our daily lives" (Peponis, 2012, p. 12), and these frameworks as manipulations of material boundaries for the purpose of differentiation and arrangement of space as both an enabling practice and an exercise of power. These manipulations allow to fold space and generate distance where there is little—such as in a labyrinth (Figure 1)—and differences to co-exist in close Euclidian proximity—such as a bedroom next to a busy street.

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[1] I acknowledge that the work in this article is concerned with form, which is not self-evident in contemporary aesthetic discourse (e.g. Frichot, 2015; Avanessian and Skrebowski, 2011). This is not intended to position aesthetics as about form further than as *also* concerning form, but there are important conceptual, theoretical, artistic, and political aesthetical issues that takes other forms than 'form' (see e.g. Rendell, 2006, p.147-152; Erharter, Schwärzler, Sircar & Scheirl, 2015; further Tschumi, 1994, 2000, 2005; Kwinter, 2001).

[2] Vidler (1992) comments, in a reflection on Hegel's (1975) writings, how "[t]he very act of impressing meaning on meaningless material, the fact that, however embedded in form, this meaning will remain always external to the material, gives a particular instability to the artistic process." (p. 123)

[3] In Hillier's (1996) terms, arguably, aesthetics rests more comfortably in 'analytic' theory, but the triad as discussed by Groys holds a more integrated relation, and arguably also points to a missing piece in syntax reasoning in techne.

Figure 1 - A labyrinth can be considered as a folding or even extension of space. Geometrically, the principle of the labyrinth is, within the confines of its overall shape, to fold the pathway to the centre so as to make the walking length as long as possible. The labyrinth performs an extreme of how architecture transforms spatial proximities by the arrangement of boundaries and connections. Here represented on a silver Drachma from Knossos, 300-270BC, (19mm, 5.41 g). Head of Hera left, wearing ornamented stephanos, triple-pendant earring, and necklace / Labyrinth; A-P flanking, ΚΝΩΣΙ(ΩΝ) "of Knossians" below. Photo: Classical Numastic Group (CNG), Public Domain.

A recognisable example of the former is the way IKEA has a visitor meander long distances created inside a box before reaching the goods for sale (e.g. Penn, 2005), whereas the latter is perhaps as most clearly demonstrated in a Lars von Trier's *Dogville* (2003), where 'walls' are simply drawn in white chalk on the floor while enacted as if real—juxtaposing at times radically different events taking place just next to one another yet as-if in different 'worlds'. While the juxtapositions of events in Dogville are rather used for drama and provocation (e.g. Laine, 2006, p.132; Sinnerbrink, 2007), it forces the viewer to face how boundaries allow close proximity of contrasting or even contradictory acts. Such allowance is further theorised by Marcus (2010), proposing the term *spatial capacity* as a means to make discursive the on-the-surface simple decisions of the number and size of units a building or a city is subdivided into. I will, however, focus primarily on the former, while recognising how as Bafna (1999) points out, this is *interdependent with* the latter.

I will begin to concretely engage with 'aesthetics and configuration' by examining select examples from Western European modernism—partially because, as Hanson (1998) notes, modernism marked a point where considerations of configurational character became more explicit in architectural thinking at large. This can, for now, be attributed to two parallel processes: the emergence of the concept of *space* as something else than 'void', and manipulable 'as such' (Forty, 2000), and the emergence of the bubble diagram and similar diagrammatic operations bringing the organisation of elements into focus in particular ways that allowed for certain forms of manipulation (Macarthur and Moulis, 2005; Emmons, 2006).

A particularly explicit example is the work of Alexander Klein. Working for the German government to develop 'scientific' norms and principles for architecture and housing (Bevilacqua, 2011), Klein developed three principles for good architectural solutions (Klein, 1927, p. 296):

1) The arrangement of movement routes and course of the walk lines (arguing that a simpler walking line is preferable to a more complex one, measured in number of turns, to minimize physical effort).

2) The concentration of movement areas (arguing that a more concentrated movement area is preferable over more fragmented solutions, in regards to comfort, well-being and spaciousness).

3) The geometric correspondence and relations of the plan elements (arguing that elements forming a graspable whole are better than a more complex and/or subdivided plan, in ensuring a coherent overall impression or perception of parts of the building).

These principles were demonstrated by examples comparing Klein's own schematics to existing cases (Figure 2). On closer study of both the figures and Klein's further writings, it more clearly becomes a question of (reducing) route complexity, (increasing) concentration of spaces, and (reducing and normalising) number of spatial elements (see also Klein, 1934, p. 99-124; Kellermüller, 1928; Bauer, 1934). Interestingly, the concepts presented by Klein hold similarities to syntactic concepts, even if they also clearly are different in, *first*, being normatively formulated, and *second*, less theoretically and methodologically robust. Thus, the way in which Klein analyses 'number of turns' lies close to how syntactic properties are discussed by for instance Peponis (2012), but Klein is concerned with norms and recommendations whereas Peponis is concerned with cognitive aspects of architectural configuration. Klein's argument forms an *aesthetic of efficiency* and *rationality* that takes several forms including number of turns.

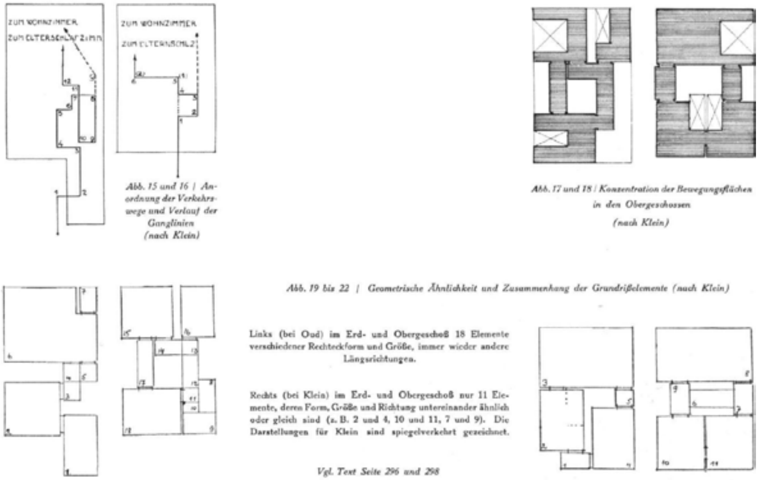

Abb. 15 und 16 | Anordnung der Verkehrswege und Verlauf der Ganglinien (nach Klein)

Abb. 17 und 18 | Konzentration der Bewegungsflächen in den Obergeschossen (nach Klein)

Abb. 19 bis 22 | Geometrische Ähnlichkeit und Zusammenhang der Grundrißelemente (nach Klein)

Links (bei Oud) im Erd- und Obergeschoß 18 Elemente verschiedener Rechteckform und Größe, immer wieder andere Längsrichtungen.

Rechts (bei Klein) im Erd- und Obergeschoß nur 11 Elemente, deren Form, Größe und Richtung untereinander ähnlich oder gleich sind (z. B. 2 und 4, 10 und 11, 7 und 9). Die Darstellungen für Klein sind spiegelverkehrt gezeichnet.

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Figure 2 - The three principles of Alexander Klein's 'graphical analysis' approach illustrated by his own drawings in *Wasmuths Monatshefte für Baukunst* und Städtebau (Klein, 1927, p. 296-298). Here, arguably, the distribution of space is put centre-stage studied under principles of efficiency and utility. (Illustrations under public domain, made available by Zentral- und Landesbibliothek Berlin).

With some liberty taken in the parallel, one can find related aspects in the work of Mies van der Rohe, in the Brick Country House (1924), the Berlin Exhibition house (1929), and the Farnsworth House (1951) (Figure 3; see also Tegethoff, 1985). In these works, manipulation of movement routes and concentrations of use areas is clearly present, from the extreme 'opposite' in the Brick Country House maximising number of turns, via the Berlin Exhibition house, towards the extreme simplicity of the Farnsworth House[4].

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[4] As can be seen in the article in *Der Baumeister* (1931) on the 1929 Berlin Exhibition titled 'Die Neue Linie', Mies did not work on these princples alone. However, as Bafna (2006) notes, there is little evidence that Mies was explicitly concerned with redefining spatial organisation in the early 1920s, and the Brick Country House holds a range of other symbolic and pragmatic properties that complicates such a notion. Furthermore, while Luciana Colombo (2015) notes that Mies was close friends with Hugo Häring and Ludwig Hilbersheimer working at the German State Research Institute on the economics of the single-storey house, there is not conclusive evidence of any actual link between the two.

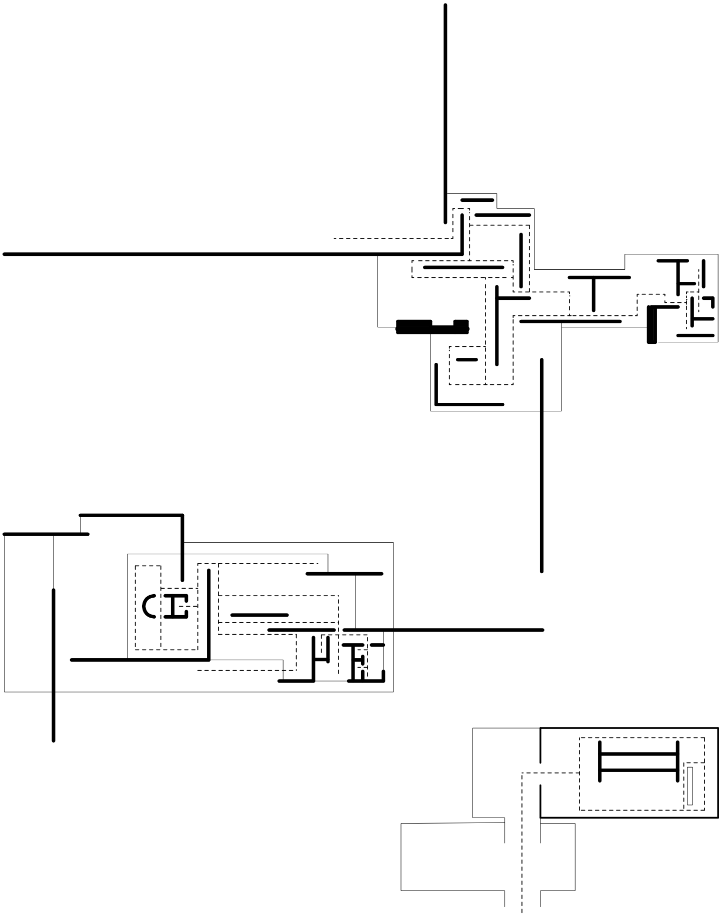

Figure 3 - Mies van Der Rohe's plans of Brick Country House (1924), Berlin Exhibition House (1929), and Farnsworth House (1951). Schematic plans with a drafted 'Klein graphic analysis number of turns line' as a dashed line by the Author.

However, this comes with a series of caveats. I do not mean to claim that Mies is deliberately commenting Klein's writings—the point is rather the engagement with specific issues of spatial differentiation, subdivision and arrangement present in architectural proposals in written and built forms. The transition from the early works with free-flowing space and the 'post 1929' free flowing plans in Mies' production noted by Bafna (2006) will for now be set aside for the purpose of focusing on the particular effect in the Brick Country house to appear, in a sense, labyrinthine, even if this *labyrinthine* character at first appear more prominent when looking at the plan as a movement choreography taking into account the geometry of connections

and boundaries than if analysing it as a convex space arrangement in a justified graph[5]. This extension of movement choreography can be further traced in for instance the Hubbe house and the Berlin Exhibition house, but subsequently seems to disappear (compare Figure 4).

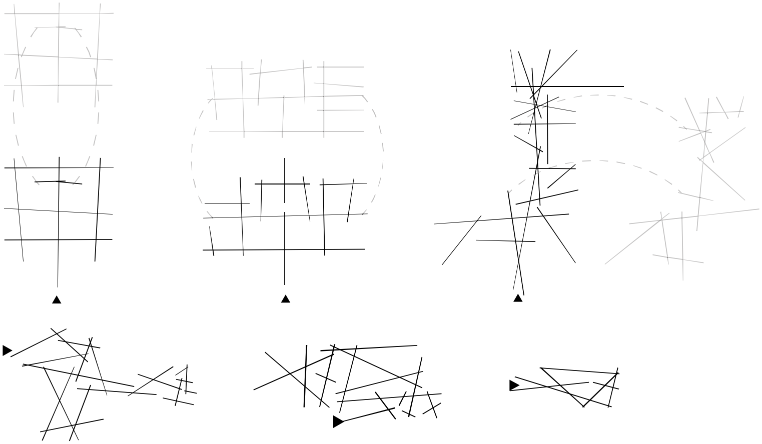

Figure 4 - Axial diagrams of three main examples from Robin Evan's Figures, *Doors and Passeges* (1978) and the three Mies' villas initially introduced in this article as axial lines. Coleshill is also discussed by Hanson (1998), and the Mies villas are discussed by Bafna (1999). Counting from the main entrance (shown by an arrow), the minimum depth to the deepest space *including* the entry line is, from top left with 2nd floor included in parenthesis: Palazzo Antonini 3 (5), Coleshill 5 (6), Red House 5 (6), Brick Country House 11, Berlin Exhibition House 7, Farnsworth House 3. If the other main entry to the Coleshill House is considered, the depth increases by one. An overview of the architectural magazine *Der Baumeister* from the years around the Berlin Exhibition (e.g. 1929, 1931b) and Klein's own *Das Einfamlienhaus: Südtyp* (1934) indicates a regular depth of published free standing houses in the concurrent period in Germany to be somewhere around four to five steps.

The labyrinth as figure is here interesting as it is the least apparently 'functional' of the examples, and in its contrast to Klein's principles. I say this without stating the purpose or the perception of the labyrinth in ancient Knossos or throughout history but rather in relation to concurrent architectural thinking. Aesthetically the process of moving into the centre and the experience—both visual and embodied (e.g. Shustermann, 1992; Dahlin, 2002; Carrol and Seeley, 2013)—along the way can be understood as important, but this understanding is also limited: when Hui Zou (2012) analyses the idea of the labyrinth (*Migong*) in Chinese building tradition, other characteristics are brought forth. In particular the sense of remoteness, utilised by the Emperor to separate himself from the public and appear as mystic. Zou links the concept further:

> "The mystic depth of human dwelling can be explained with the ancient concept ao, which, according to the architectural treatise *Yingzao fashi* (The Principles and Patterns of Building; 1103), means "remoteness," and its semantic root is related to the space for sleeping. In the ancient dictionary *Erya* (ca. third century bce/to first century), the *ao* is explained as the south-western corner of a bedroom, which marks the remotest spot of a domestic interior. In *Shiming* the *ao* is described as a residential room wherein remoteness can be perfectly contained." (p. 81)

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[5] It is of course not a coincidence that the Labyrinth and the Brick Country House are featured on the front page of Psarra's *Architecture and Narrative: The formation of space and cultural meaning* (2009), as well as an introductory figure to the conclusions. Justified Graph: See Hillier and Hanson (1984).

Remoteness is the condition for a place where the mind and body can rest, and it is in *remoteness* one can be as most oneself and in harmony with the world. As Zou continues to show, deep and remote spaces as present in a wide range of Chinese architectural motifs, from graves to imperial gardens to housing. Remoteness, here, is different from a generic 'privacy' through a material boundary as in a regular, contemporary 'western' apartment in its procedural qualities of distance and folding, and the notion stands in direct contrast to how Anthony Vidler discusses relations between the labyrinth and the *unhomely* (and uncanny) in De Quincey and Piranesi (1992, p.37). What Zou points to, is that while 'remoteness' could be argued for in functional terms in structuring relations between 'private' and 'public', there are additional aesthetic qualities in remoteness that are considerably different from that of separation.

While not claiming that Mies Brick Country House *is* a labyrinth, it is possible to draw parallels to how experience is structured and what kind of experiential, functional, and habitual qualities are embedded in the building considered as a place to live in. From this point of view the Brick Country House and the Farnsworth House are polar opposites—while the former extends, folds and makes distant, the latter minimises, compresses and integrates—but both clearly play with how geometry and space interplay with lived architecture. If the Brick Country House is investigating how to architecturally provide spaces like in a regular *Landhaus* without the use of doors, the Farnsworth House is an investigation of minimizing walls[6]. Here, one can relate to Hillier's investigation in 'Is architecture an ars combinatoria' in *Space is the Machine* (1996, p.275-334): the Farnsworth solution is analogous to an operation where as little wall as possible has as large differential effects as possible.

3. NARRATIVES OF MOVEMENT AND VISION: TOWARD HABITS AND DISPOSITIONS

It bears repeating that I do not intend here to suggest that Mies villas can be understood simply as configurative investigations; geometry, material, views and vistas (compare to Klein, 1934, p.98-105), reflections, construction units, free-flowing space, and a range of other questions must be considered, including what kind of family (real or imagined) Mies was designing for. These qualities, however, are partially linked to the configurational properties of Mies' architecture. For instance, Shophia Psarra (2009) shows how the Barcelona Pavilion stages views and makes use of reflections in a manner that is interlinked with how space is configured by walls and objects. Psarra offers a more directly comparable example in her analysis of the difference between the Acropolis and the Parthenon, where the former early on offers views of the 'complete story', and the latter is predominantly experienced sequentially via partial views continuously evolving as one moves through the complex:

> "Thus, the entrance to the profane part of the acropolis was 'symmetrical' with the entrance to one of its temples. In contrast, the Parthenon entrances were hidden and could be accessed through a set of intervening spaces and changes in direction. Visitors would also assimilate a larger narrative consisting of the two buildings and their relative position in the precinct." (p. 29)

In some aspects, the labyrinth is the extreme figure for the latter experience: the sequenced, partial, folded, and extended, holding clear narrative qualities as well as quite distinct from the overview (see Tschumi, 1996)[7]. But it also points to an important *difference* between the Knossian labyrinth and Mies' Brick Country House: while one folds space into a spiral, the other folds space so as to provide a series of views and vistas, breaking up the material boundary to let vision flow free to the exterior—even if it only in minor parts of the building offers views between locations inside the building itself.

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[6] One might speculate that one reason for the comparatively complex spatial structure of the Brick Country house is precisely the conflict of solving a traditional *Landhaus* plan, the influence of Hendrik Petrus Berlage, Frank Lloyd Wright and the *De Stijl* movement (e.g. Colquhoun, 2002; Bafna, 2006), a concept of free-flowing space, and walls and openings as separate entities.

[7] Tschumi comments: "The nature of the labyrinth is such that it entertains dreams that include the dream of the pyramid." (1996, p.49) One point in this quote is the relation between complexity and overview, or, being lost and seeking a map. It is *also* a comment of the inadequacy of such overviews and maps in being unable to grasp the full complexity of the labyrinth.

This points to another question I will address before moving towards conclusion, one that can be further emphasised by how Peponis and Bellal (2010) in their analysis of Fallingwater show that Frank Lloyd Wright's building has at least three centralities, depending on whether on focuses on movement or vision, and whether one includes the terraces or not. This depends on the complex relations between visibility and permeability, which at times take on contradictory properties, such as that one is *closest* to everything in the centre of a square, but has *best overview* from one of its corners (Hillier, 2003). The reason to address this, is how they form interrelated parts of architectural experience, and a discussion on configuration and aesthetics is by necessity must recognise the challenge this poses, and the architectural qualities it entails. Qualitatively, we can understand such differences as disjunctions (Tschumi, 1996) generating complex sets of configurational relations.

Psarra (2009) develops this regarding not only the Barcelona Pavillion, but also sir John Soane's museum structuring reoccurring views of artworks throughout the building. She demonstrates how in both cases, there are important effects of this interplay that are central to how they construct narratives and how they create relations to both the building and one's own role in it, as well as how one is to relate to the sculptures. Borrowing an analysis from earlier work (Koch, 2012) and adding a three-dimensional illustration, the effects can be illustrated in how a serial configuration of permeability relates to on the one hand adjacency, and on the other hand, as potential disjunctions of visibility and permeability when being folded around a courtyard in a two storey-building (Figure 5).

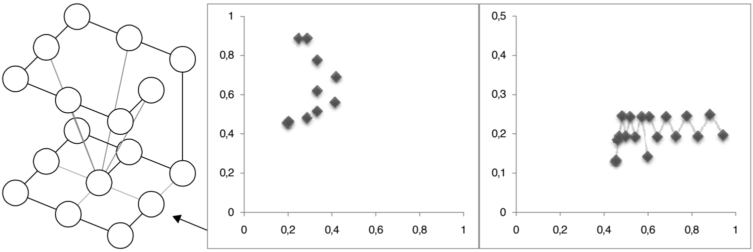

Figure 5 - Analysis of disjunctions of relative asymmetry in an 'ideal' configuration of an atrium building with a 'labyrinth' configuration. Left: The configuration analysed where a black line represents movement access and a grey line visibility access. Middle: Between adjacency (x) and permeability (y). Right: Between permeability (x) and visibility (y). Scattergrams from Koch (2012).

Structuring of such relations sets conditions for how relations between inhabitants, between inhabitants and visitors, and between inhabitants and an exterior public is both conditioned and communicated as I have earlier closely examined in the Adolf Loos' house for Josephine Baker (Koch, 2013a), and de Holanda (2009) has investigated in Oscar Niemeyer's architecture. In Loos' proposal, one finds a quite particular and different set of social relations embedded in the building, which challenge notions of privacy, exposure and control, and which repeatedly invites speculation by a continuous play of hiding and exposing. These disjunctions and how they are treated form particular aesthetic qualities embedded in architecture which unfold through dynamics of visits as well as over time in continuous inhabitation, and—if we follow Benjamin's argument—are appropriated in distracted experience and *internalised*, forming habitual relations and understanding of the world and one's relations in it and to it, in addition to how it structures habits and behaviours.

A perhaps more straight-forward approach can be found in Evans (1978) discussion on plan-ideal relations as materialised family relations and notions of privacy in the Italian Renaissance villa—in particular Andrea Palladio's *Palazzo Antonini* in Udine—and the 19th century English

house—in particular Philip Webb's the *Red House* in Bexleyheath, London. He demonstrates how they express distinctly different positions regarding individual privacy, household composition, and the spatial frameworks for enactment of social relations that constitute the households: whereas the Italian Villa has *no* rooms with only one entrance, *most* rooms in the Red House have only one entry—necessitating the use of corridors and passages. In this configurational difference, they represent different *ideals* of life, of family, household, and a range of other things. The particular aesthetic qualities of the Brick Country House or the Baker House, however, are only possible to achieve by the combination of specific foldings of permeability space in relation to specific, interrelated opening and closing of visibility conditions, that stages the arrangement and interrelations of the vistas it provides.

3. HABITS OF INHABITATION

So, if we consider the labyrinth here to, first, be an elaboration of cultural and experiential significance and purposes, which has both traditional and deliberate roots, we can see the labyrinth as an aesthetics of certain intentions and effects realised through architectural configuration made concrete through a geometry of folding. Second, we see the labyrinth from the point of view of *habit*, as discussed by Ballantyne (2011), in that it builds both habitual relations to that which the labyrinth holds, the presence and significance of labyrinths as such, and as producing the habitual understanding of a visit to such a place to consist of walking through a labyrinth. In Benjamin's terms, the labyrinth becomes *absorbed* into our understanding of a place, and into a broader understanding of architecture and society.

If we return to the complex relation between a Kantian and pragmatist aesthetics, particularly from the point of view where Kant argues that the purpose of aesthetics is to *train the way we look at the world*, additional questions rise. Acknowledging that this is a somewhat unorthodox link made—Kant speaks specifically of the engaged experience with art—it allows to consider the absorbed aesthetics [of the labyrinth] into individuals and culture, or the transmission of cultural norms via architectural configuration as discussed by Hanson (1998) or Markus (1993), to not only be a communication of norms and values, but as a fostering of a way to view the world, and consequently, ways to view the world *instead of other ways to view the world*.

Zou's example of the Chinese garden as operating through remoteness qua the labyrinthine is perhaps particularly clarifying in such a view. Relating to gardens, nature, individual and collective, this is another view of what a garden or nature *is* than in the open fields of many public parks, that is 'habitised' through the specific aesthetic arrangement and manipulation of the garden space. A comparison can be made to Japanese gardens, or perhaps more concretely the temples and paths between them around the valley of Kyoto, or to certain notions of medieval or self-organised streets (Johnson, 2013; Ingraham, 1998).

4. SYNTACTIC AESTHETICS

Analysis developing similar lines of reasoning is definitely present in syntactic discourse also outside of the aforementioned works by Hanson and Markus. However, with some notable exceptions this tends to be remarkably limited to museums (e.g. Bafna, 2012, 2013; Peponis, 1993; Peponis et al., 2015; Psarra, 2010, 2014). One reason for this could be that whichever way one may look at it, it can hardly be disputed that one of the central purposes of art museums is to curate aesthetic experiences, but as Tzortzi (2011), Psarra (2009) and Zamani and Peponis (2005) and others have demonstrated clearly the configurations of museums and artworks within them participate in a range of processes that defines not only specific pieces of art, but their contextual belonging to categories, how categories are arranged and interrelated, their fleeting or well defined boundaries—or as Wöllfflin (1950) puts it: linear or painterly—and how experience and interpretation depends on the configurational setting[8]. Tzortzi and Hillier (2016) provides a particularly interesting example in their analysis of museums of performing

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[8] This links clearly to both artistic practices such as by Asher, Wilson and Haacke, and to other research into curatorial practices and museum architecture as discussed by Bourdieu and Darbel (1991), Bennet (1995), von Hantelman (2011), Kaye (2000), and Buskirk (2003), to name a few.

arts. Their argument, in the very brief summary that can be brought in here, is that certain performative experiences can be alluded to or reminded of through certain configurational characters of the museum layout that would not emerge in other configurations—in particular, the effects of 'ab'-space pairs (Hillier & Hanson, 1984) to stage the approach and engagement with the exhibited material in particular ways via particular narratives.

Through these works, it becomes clear how notions of aesthetics guide both the design of museums, and recursively, the notions of aesthetic experience and in the extension, notions of art. That is, art museums offer concrete examples of several layers of aesthetics that form an integrated discourse on aesthetics, art, and exhibition through one another, and it becomes clear how spatial configuration participates concretely and directly in this negotiation and discussion. However, an extension of the concepts developed in this research into a wider discourse on architecture seems not only to hold potential, but to be necessary. This said, these studies offer key insights into a closer understanding of the relation between architecture, engaged and distracted experience, habits, and dispositions towards 'the world'.

If we then return to Evans discussion on the pre-modern and modern architecture. If Evans is correct in his claims that there are shifts in the principles by which architecture is considered from geometrical symmetries and proportion to functional considerations and use-adaption, this would suggest altered aesthetic dispositions not only by architects, but by inhabitants, users (another term non-existent in pre-modern architecture), and a wider societal culture. That is, a shift in aesthetics to express 'use' or 'function' may, whether successful or not, begin a process where the absorbed notion of architecture is one of 'use value' or 'facilitation of function'[9]. With such a disposition even if we *can* speak about the labyrinth as fulfilling a *certain* experiential function, it is an alien figure that goes against the way habit and disposition conditions views of the world, the material environment, and architecture. Instead, we expect that architecture facilitates certain functional processes which we through habit and absorption have come to consider as ways in which architecture should operate. Considering how complex, contradictory, and changing the 'social' world is, and how architecture (as any artefact) is inadequate to provide absolute solutions to them, or even solutions where all the different habits, practices, relations and activities are given equal possibility (Markus, 1993; Koch, 2013b), this points to additional complexities. As a quite pragmatic but clear example, one can turn to how Krippendorff (2006) discusses such an ostensibly simple artefact as a milk crate:

> "Milk crates are intended to transport milk to grocery stores, but designers can hardly prevent unintended uses: as bookshelves, playthings for children, bins to store tools, dividing walls, stepladders, or bicycle baskets. For a homeless person, a milk crate can hold priceless possessions. Tied to a pole with its bottom removed, it is a basketball basket. In the hands of an angry person, it can become a weapon." (p. 108)

Peponis (1989) discusses functionalist apartments in a similar vein in 'Space, culture and urban design in late modernism and after' in *Ekistics 56*, noting how they have come to be used by the inhabitants in quite reasonable but often radically different ways than the prescribed intention of the architects. Whether this is a failure or not comes down to the extent to which we expect, in the simplest sense, a milk crate to be used to carry milk in it. Rather than predicting or determining certain modes or ways of use, thus, one can argue that a legacy of modernism is the understanding that architecture should be evaluated based on the extent to which its subsequent use conforms to design intentions. Be that as it may, the argument here considers shifts in aesthetics understood as dispositions (views of the world), as engendered through both 'distracted' and 'engaged' experience, in part fostered by architectural solutions but with a limited capacity to determine it (e.g. Markus, 1993; Tschumi, 1996; Kaye, 2010). I here deviate from Ballantyne's discussion in the particular sense that he makes closer ties between architecture responding to habits and 'good' architecture, whereas I am more concerned

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[9] Wigley (1995), Hillier and Hanson (1984) and Scott (1998) all point to the importance to understand modernism not as *solving* function but as *an aesthetics of function*, which while not central to the discussion of aesthetics and configuration specifically, links to notions of relations between habits, dispositions, and understandings of architecture.

with recognising them as modes to understand other architectures and consider alternate possibilities. Through the above discussion, arguably, the presence of such relations between such dispositions and architectural configuration are clear.

5. CONCLUDING WORDS: CONFIGURATION AND AESTHETICS

This article has intended to discuss ways in which architectural configuration, or spatial configuration, can be understood as aesthetics, addressing the two sides of syntax theory outlined in *The Social Logic of Space*—the way material boundaries are manipulated to differentiate, define, and link *space*, and how social norms, structures, habits and practices can be linked to it. The reason, as stated in the introduction, is that amongst many other things, architecture is an aesthetic discipline, and architecture is experienced also aesthetically (in whatever way one defines it). In line with the general thrust of syntax research, focus has been put on 'aesthetics of the everyday' rather than the more engaged form of aesthetics of for instance a museum visit, as Benjamin differentiates it. This is not meant to say that studies of architectural configuration cannot contribute to the latter, but arguably this side of aesthetics is more consciously engaged with in the field as in for instance the works of Baffna, Peponis, Psarra, Tzortzi, and Zamani. Such an engagement with configuration, and the society-space relation, opens up for other interpretations of findings as well as, arguably, lines of reasoning pivotal for a closer engagement with both architectural theory and practice. It highlights potential aesthetic positions embedded in *ways of interpreting and approaching* configurational analysis. Important for this reflection is that in architecture, a 'non-aesthetic' position is not possible, especially not in the way discussed in this article—and even if such a position was attempted, it has direct purchase on aesthetic results that need to be recognised and further discussed.

It is *not* a suggestion that space syntax can solve aesthetics or should become an aesthetic field as a whole. Rather, the above shows how an approach to architectural configuration from the point of view of aesthetics allows for a range of critical discussions to be held, and that in understanding architecture aesthetics, configuration is *one* aspect where syntactic analysis could contribute. While, as Hanson notes there are clear notions of configurational play in modernism in that the play between *permeability* and *visibility* becomes an important aspect, other periods and aesthetics hold other principles, such as demonstrated by for instance Evans. Sometimes configurational reasoning is explicit, as in the works of Alexander Klein, with remarkable similarities to syntax theory with some key differences including its normative approach; norms in clear contrast with Zou's discussion of remoteness. In this sense, however, it is arguably possible to discuss *configurational aesthetics* of periods as well as individual works, architects and offices. As Psarra (2009) does regarding Robert Soane's museum, as Koch (2013a) does regarding Adolf Loos' house for Josephine Baker, as Bafna does regarding the Seattle Public Library (2013), as Peponis et al. (2015) do regarding conceptual shifts in design, as Tzrotzi (2011) does regarding museum curation, as Aragüez and Psarra does regarding SAANA (2015), or as Stavroulaki and Pepoinis (2003) discuss the narrative of statues in Castelvecchio.

ACKNOWLEDGEMENTS

The writing of this article has been supported by Swedish Research Council Formas through the research project Architecture in the Making [2011–75].

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#163

ROAD CENTRE LINE SIMPLIFICATION PRINCIPLES FOR ANGULAR SEGMENT ANALYSIS

IOANNA KOLOVOU
Space Syntax Ltd
i.kolovou@spacesyntax.com

JORGE GIL
UCL
jorge.gil@ucl.ac.uk

KAYVAN KARIMI
Space Syntax Ltd
k.karimi@spacesyntax.com

STEPHEN LAW
Space Syntax Ltd
s.law@spacesyntax.com

LAURENS VERSLUIS
versluislaurens@gmail.com

ABSTRACT

Angular segment analysis is one of the most fundamental analyses in space syntax practice that helps understand movement, land-use and other socio-economic patterns. It was initially applied in axial segment maps and later was used in road centre line maps as an attempt to overcome the 'segment problem' (Turner, 2005). Furthermore, the growing need to examine large urban systems has led to the wide use of road centre line maps instead of the previously hand-drawn axial maps. However, this transition to such datasets has lacked systematic studies on what is required to convert a road centre line map into a segment map, in order to produce reliable results of the angular segment analysis. To date, no consensual methodology has been developed within the space syntax community.

This paper attempts to clarify what a road centre line segment represents spatially and suggests principles and rules to simplify a road centre line map to a segment map. Based on previous experience, the simplification mostly relies on the following two principles: reducing the number of nodes in the dual graph representation of a street network; optimising the angular change between adjacent nodes of the dual graph when space allows it.

In addition to the above general principles, we discuss rules for special and complex cases, e.g. roundabouts, underpasses, bridges etc. To evaluate these rules and principles comparisons are carried out between traditional axial and RCL unsimplified and simplified segment maps, to develop a good understanding of how changes in dual graph representation of a street network can affect space syntax measure of 'choice'. Correlations of angular segment choice values are performed in order to evaluate which simplification technique can approximate better the axial representation of actual human activity.

The results show that using a raw road centre line data set raises several inconsistencies in the analysis results, and the progressive application of the different simplification techniques brings these results closer to those of a traditional axial segment map, and thus to a better representation of socio-economic activity. The purpose of simplification is to minimise inconsistencies to ensure maximum accuracy in the results of angular segment analysis.

KEYWORDS

Simplification, road centre line map, angular segment analysis, GIS

1. INTRODUCTION

1.1. MOTIVATION

Given the growing need to grasp the complexity of large scale systems and the availability of big data, such as Road Centre Line (RCL) maps, techniques need to be developed to overcome the gap between different network representations of urban streets and guarantee the rigorous results of the analysis. As Dhanani et. al. (2012) emphasise the big availability of RCL maps can promote the engagement of space syntax to a wider audience and thus expanding space syntax research and applications.

RCL maps cover almost the whole of the globe and are usually free (e.g. OSM; TIGER; OS) and despite their inconsistencies in data representation (Dhanani et al., 2012, p.5) previous research and application have showed that syntactical values can be approximated if derived from a RCL map (Dalton 2001; Turner, 2007).

One of the most popular analyses in space syntax is segment angular analysis (Turner, 2000). Angular segment choice or betweenness centrality as known in graph theory, is a graph measure that can describe the potential of movement of an axial segment map based on its configurational properties. Angular choice is calculated as the total number of least angular paths that pass through a segment, when every segment in the system is an origin and a destination. While studies have proven that angular segment choice can be associated with movement patterns (Turner 2005, p.146; Hillier & Iida, 2005), commercial land uses, land use density, town centres' vitality, high streets' patterns (Chiaradia et al., 2012; Vaughan et al. 2010) and property values (Chiaradia et al., 2013), there is no systematic approach or established methodology of how angular choice analysis should be applied when using a RCL map, leading to possible inconsistencies in representations and thus misleading or poor analysis outcomes.

Therefore, we are interested in exploring the effect of different street network representations on angular segment choice. We hope this paper to contribute to validate the suitability of RCL maps for angular segment analysis and make space syntax analysis more easily approachable by different urban analysts eliminating doubts on the analysis outcome. The first question posed is if simplification is needed. And the second is what simplification process needs a RCL segment map to approximate an axial segment map.

1.2 MAIN OBJECTIVES

Although RCL maps are widely used in space syntax, there is limited research on how RCL maps can be used for angular segment analysis in particular. Questions about the suitability of RCL maps started being posed soon after the introduction of angular segment analysis by Turner in 2000, but to date no consensus has been reached.

The paper's main objective is to test whether RCL maps are suitable for angular segment analysis and experiment on choice measures variations between different street network representations. Based on the assumption that RCL geometric relations can be transformed to simulate axial geometric relations the paper seeks to establish a coherent methodology of applying angular segment analysis to RCL maps. Namely, we hope to shed light on what a RCL segment may represent spatially, how this differs from an axial segment representation and how a RCL segment should be treated prior to angular segment analysis.

The first section begins with setting the background of this research paper by overviewing previous studies using RCL maps with space syntax analysis. The next section presents the method undertaken by the authors, using comparative analysis and statistical methods. The comparisons are made between axial and unsimplified RCL maps and between axial and simplified RCL maps. The intention is to go through a series of simplification processes of a RCL map, and study their impact on the analysis. We believe that this method reveals if geometrical modifications to RCL data are needed prior to analysis and how these can be formulated in a coherent simplification process.

2. BACKGROUND

2.1 ANGULAR SEGMENT ANALYSIS IN SPACE SYNTAX

Axial maps have been used for 30 years to analyse the configuration of urban spaces. The analysis of their network properties has proven to be good proxy for movement, land use, interaction, land value and crime patterns. Their unique representation as the longest and fewest lines of visibility and accessibility in continuous spaces is translated in a dual graph where every segment is a node and every connection between segments is an edge with metric, topological or angular cost (Hillier and Hanson 1984). They are usually hand-drawn which can be a time-consuming process especially in case of metropolitan areas.

The angular segment analysis in particular has been used since the beginning of the millennium and is related to the cognitive behaviour of a person moving in space who is likely to choose the least angular path when getting from A to B. Assuming that every segment is an origin and every other segment is a destination choice is the total number of overlapping trips passing through a segment (Turner, 2000). Calculating choice can be computationally very intensive but the value of angular analysis (Turner, 2000) is that it is a more fine-grain analysis than mean depth analysis, where the focus is moved from the average number of turns to the sum of angular change in one's journey.

Turner (2000, p.8) when introducing angular analysis points out that 'angular analysis does not actually fit as succinctly as this into the space syntax paradigm, as the layers which form 'representational' and 'configurational' are not clearly defined in angular analysis.' He continues by highlighting areas where problems of representation can skew the results of this method; 'firstly, the axial map is drawn by hand and therefore the result depends on the skill of the cartographer. Secondly, there may be unnatural weighting to highly spatially complex areas of the space (where large numbers of axial lines are required).' Such questions have opened up the exploration of other representations of the street network.

2.2 ROAD CENTRE LINE MAPS IN SPACE SYNTAX SO FAR…

The discussions on representational issues of axial maps for angular segment analysis started in parallel with the conceptual and computational advances on large scale urban analysis. Space syntax community gradually shifted to RCL maps, in an attempt to look for other datasets that can describe the configuration of street networks in a similar fashion as the axial maps. RCL maps, provided by web mapping services either authoritative (e.g. OS, TIGER etc.) or voluntary (e.g. OSM) are widely used for mapping the street network of cities, analysing its properties and simulating urban activity patterns.

RCL maps represent networks of different modes of movement and not spatial and visual connections as axial maps. In comparison with the axial representation, the RCL representation does not take into account the width of a street as an axial line would do. In a RCL map every street segment between junctions is drawn as the medial axis of the street. Another major difference is that a RCL starts and ends at an intersection where it meets other RCLs. An axial line does not break at an intersection if the space it is traversing is continuously visible and accessible. This means that the axial segments will have no angular differences between them, whereas the RCL segments will still have small angular changes between them. For axial lines space is continuous when is constantly visible and accessible, whereas for RCL space is

continuous between decision points i.e. intersections of roads. Despite such fundamental differences, RCL maps continue to gain acceptance within the space syntax community (Dalton et al., 20003; Turner 2005; Dhanani et al 2012).

Systematic research on the effect of applying axial and segment analysis on RCL maps in space syntax analysis started the last 15 years and has illustrated encouraging results. Dalton's (2001) research supported Turner's idea (2000) to explore new graph representation of street networks. He suggests that 'it might be best to begin by reviewing if it is necessary to abandon axial lines when looking at new forms of processing.' His research shows that the integration of GIS data with axial analysis may benefit more from other representations than the axial map.

Another piece of research published by Dalton et al. two year later, showed that when 'traditional syntactic analysis [is] applied directly to TIGER representations of US cities [it] will give results that are quite misleading as compared to the results that would have been obtained by normal syntactic analysis.' Despite that when fractional analysis was used to approximate topological axial analysis in a RCL map, the two representations became syntactically similar. This has provoked other research paradigms where RCL maps become to take over. Turner in 2005 further questioned the necessity of axial segments over RCL segments. He showed that angular segment analysis can be applied in RCL maps and produces good correlation with vehicular movement data although he points that when moving from smaller to radius n, the correlation becomes weaker.

Although big steps were made to validate RCL representations in configurational analysis, representational issues were still acknowledged within space syntax community. Attempts to generalise the values of choice to allow comparisons between different systems have highlighted the importance in the inclusion of depth in the calculation of choice (Hillier et al., 2012). Other methods like weighting choice values by segment length have been attempted (Dhanani et al 2012; Dalton 2003) to "compensate for the numerous segments that RCL data have" (Dhanani et al 2012, p. 9). Dhanani's et al. comparative analysis of axial and two RCL maps - ITN layer from Ordnance Survey (OS) and OpenStreetMap (OSM) - has highlighted that the principal network structure is identified by all three types of maps at radius n, but the smaller the scale the greater the differences become. They showed that "the representation of the network changes the analytical result" (p.17) but different street network representation may have more similarities than expected; "osm, itn and axial models all scale over space in a consistent fashion". Thus, the issue of 'readiness' of a RCL map that Dhanani et al. (2012) raise, is the main focus of this study.

3. THE METHOD

The maps used for this study are an axial segment map of London provided by Space Syntax Ltd to be compared with two types of free RCL maps of London, Open Roads from Ordnance Survey (www.ordnancesurvey.co.uk), the UK government topographic and mapping agency and OpenStreetMap (OSM), a free volunteered geographic information (VGI) online mapping service, using data samples obtained from GEOFABRIK (www.geofabrik.de).

In preparation for the experiment, the maps are cropped to 7 kilometres radius around Central London. This is to ensure that we will still be able to study city-scale radii and analyse the networks in reasonable time using DepthmapX. The RCL-OSM dataset is filtered based on the 'fclass' attribute so that all lines that do not correspond to pedestrian movement are not included, with such categories as: 'cycleway', 'track_grade' and 'unknown'. Categories 'footway', 'pedestrian' and 'path' were also removed as they were often over representing spaces such as sides of pavements or footpaths in parks of minor city-wide importance.

Moreover, all RCL maps are segmented using NetworkSegmenter QGIS plugin (Versluis and Gil, 2016) and cleaned using RoadNetworkCleaner QGIS plugin (Kolovou and Gil, 2016). The cleaning process involves validating the geometries so that they are suitable for GIS analysis, for example invalid geometries, including points, duplicates and overlaps and isolated geometries. The RCL-topology-cleaner also corrects topological errors of RCL maps. These errors might be

lines intersecting at common vertices or broken lines between intersection. In these cases, the tool breaks the lines at the shared vertex and merges lines into polylines from intersection to intersection. Another important part of this process is snapping disconnected geometries. As Dalton et al. (2003) point out "one line segment might terminate at coordinates 10222.0222, 3329983.2 and another might begin at coordinates 10222.0221, 3329983.2" which creates invisible disconnections between segment. For this reason, a precision of 6 decimals has been applied as a snapping tolerance to all maps.

It should be noted that the necessity of the RCL-topology-cleaner tool mostly applies to OSM, as the dataset is not as rigorously validated as the Open Roads layer. This is expected due to the VGI nature of OSM; different volunteers usually have different perceptions of space, different views on when a space should be included or not and different ways of drawing.

The study is made up of three experiments comparing between axial and RCL where the RCL maps are: unsimplified (Open Roads and OSM); simplified with Douglas-Peucker algorithm (Open Roads and OSM); simplified with Douglas-Peucker algorithm and proposed modelling rules (only Open Roads).

The first experiment uses the Open Roads and OSM unsimplified. The second experiment simplifies the RCL maps using the Douglas-Peucker algorithm. This algorithm is used in cartographic generalisation to reduce the number of vertices that represent a digitised line. Here we use this algorithm to reduce the number of vertices of polylines between intersections. For the final experiment, we take the Open Roads map simplified with Douglas-Peucker algorithm and further simplify it by hand. A set of five modelling rules are applied which have come up as cases with special particularities on how angular change may affect choice at local and global conditions. The rules follow the principles of the axial map, where the fewest and longest axial lines are drawn. Below follows a short description of each rule and examples in figure 5.

1. **Roundabouts:** Roundabouts are simplified with straight links between consecutive entries or exits to the roundabout. Roundabouts with buildings in the middle can be treated similar to urban blocks.
2. **Staggered junctions:** When two almost parallel lines can be approached by a slight change in direction of movement a diagonal line can be drawn.
3. **Squares:** Connections are drawn between all "entry" and "exit" points to a square. If two points are directly visible and accessible a straight link is drawn between them. The cartographer should attempt to draw the least number of lines with all possible connections.
4. **Underpasses, overpasses and bridges:** This rule is the easiest to implement as lines of RCL maps cross but not intersect where there is a level difference. Thus, the only requirement is when using DepthmapX that no unlinks layer is loaded and that the RCL map is directly converted to segment map.
5. **Parallel lanes:** In a RCL map different lanes typically found in motorways and highways are represented by two parallel lines. An axial map is not directional. In these cases, parallel lanes are drawn as a single medial line.

The comparisons across the three experiments are made for basic descriptive statistics and statistical analyses: **primal graph statistics** - number of segments, numbers of intersections, total segment length; **dual graph statistics** - number of nodes (segments), number of edges (segment to segment connection), connectivity distribution, angular connectivity distribution; **analysis correlations** - spearman rank correlations between angular segment choice at 800m, 1200m, 2000m, 3200m, 5000m, N.

To make comparisons between analysis values of an axial and a RCL map, link layers are created in PostgreSQL and PostGIS software using SQL scripts to spatially link the values of a RCL segment with the corresponding values of axial segments, when they are no more than 15 meters apart and do not have difference in angle greater than 14 degrees. Below is an example of such linkages for Open Roads and OSM.

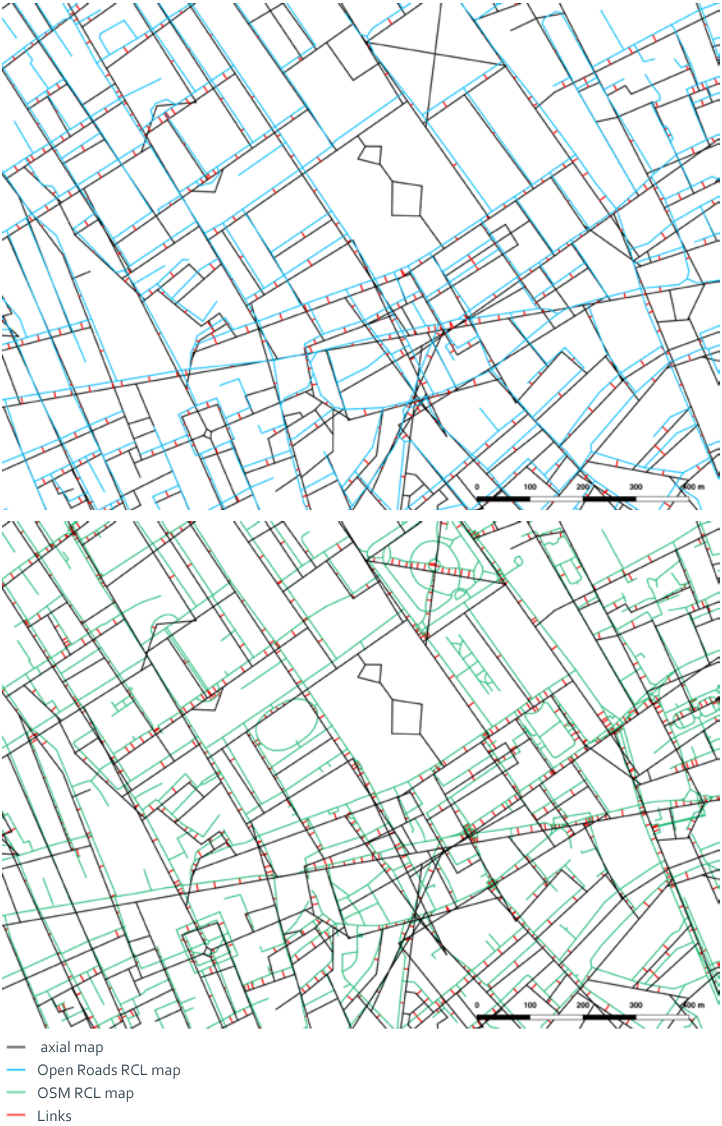

Figure 1 - Each RCL segment is linked to one or many axial lines

4. THE RESULTS

4.1 EXPERIMENT 1: AXIAL AND UNSIMPLIFIED RCL MAPS

Beginning with comparing the axial and the unsimplified Open Roads and OSM maps of London, their primal and dual graphs look very different (table 1). An OSM map has many more segments than an axial or an Open Roads map and a lower average angular connectivity in its dual graph representation. Moreover, most of the connections between segments of the three maps are at 0 or 90 degrees, but the percentage of connections to the total changes. Axial maps have many more segments connecting at angles close to 0 degrees, whereas the RCL maps have fewer connections at 0 degrees and more connections at 90 degrees (figure 2). Urban space in RCL maps is represented more fragmented and not as continuous as in the axial map.

Map	**Primal Graph**			**Dual Graph**			
	number of nodes	number of edges	total segment length (m)	number of nodes	number of edges	connectivity (average)	angular connectivity (average)
Axial	43,422	66,090	3,185,002	66,090	147,979	4.48	60.29
Open Roads	51,837	60,854	2,880,571	60,854	96,046	3.16	52.88
Osm	173,469	194,445	4,330,880	194,445	280,616	2.89	45.83

Table 1 - Comparing the structure of the primal and dual graphs of an axial, an Open Roads RCL map and an OSM RCL map.

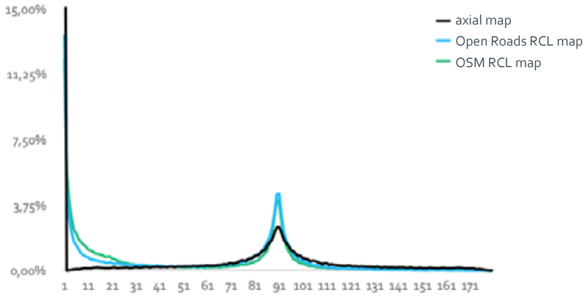

Figure 2 - Angular connectivity distribution of dual graph edges for axial segment map, Open Roads segment map and OSM segment map.

In addition to the chronological differences of the maps in comparison, another important factor to consider is the resolution of the maps. A traditional axial map has less number of segments than an OSM map and more than an Open Roads map. This certainly draws a very clear conclusion about the nature of the RCL maps. Since Open Roads is a dataset that originally comes from a detailed and complete dataset of the network in UK (OS ITN layer), it is a more generalised representation of the street network that has already undergone some process of validation and filtering. On the other hand, the voluntary nature of OSM is evident by the varied resolution in the geometrical representation of spaces. For example, the bridge in figure 3 is just a single straight segment in an axial map whereas in the Open Roads map it consists of three segments and in an OSM map of ten segments. In addition, the southwest river walk is absent in the Open Roads map, but drawn in much detail in the OSM and partly drawn in the axial map.

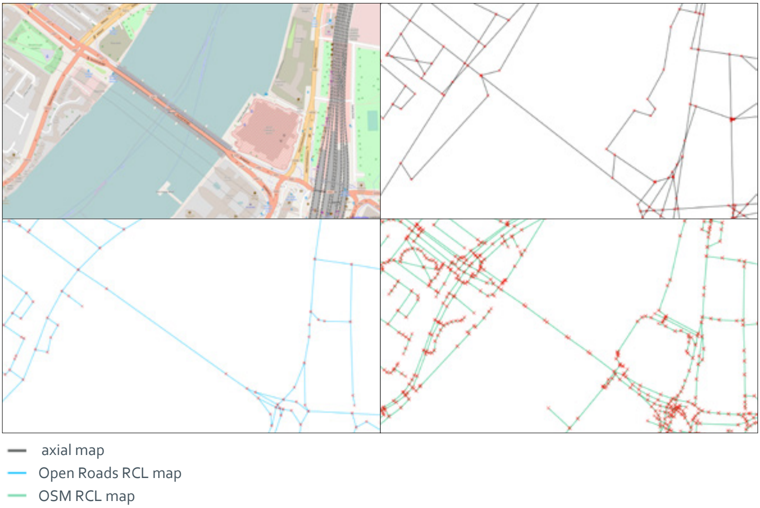

Figure 3 - Differences between the representation of spaces in axial and RCL maps. (1) OSM web map (2) axial map (3) Open Roads map (4) OSM map

Acknowledging such inconsistencies, the first question to answer is if the angular segment analysis of a RCL map using DepthmapX can produce similar results to an axial segment map analysis. Comparing choice values of the axial segment map and the RCL maps (table 3), the analyses look very dissimilar with more eminent differences at smaller metric radii. The weak correlation of the results of angular segment choice analysis between RCL maps, especially for a RCL- OSM, implies that it is probably inaccurate to analyse a RCL map as a raw dataset.

4.2 EXPERIMENT 2: AXIAL AND SIMPLIFIED RCL MAPS WITH DOUGLAS-PEUCKER ALGORITHM

Our second question is if RCL maps can be transformed to approximate an axial map. For this experiment, we use the Douglas-Peucker algorithm to transform the RCL maps. This transformation can minimise the excessive fragmentation of a continuous space as represented in a RCL map, especially one coming from OSM. As shown in figure 4, a rather uninterrupted continuous route from A to B is shown as four line strings with small angular changes between them. With Douglas-Peucker algorithm the angle when moving from A to B can reduce to even 0 degrees when a tolerance of 15 is used. Similar for journey from A to C.

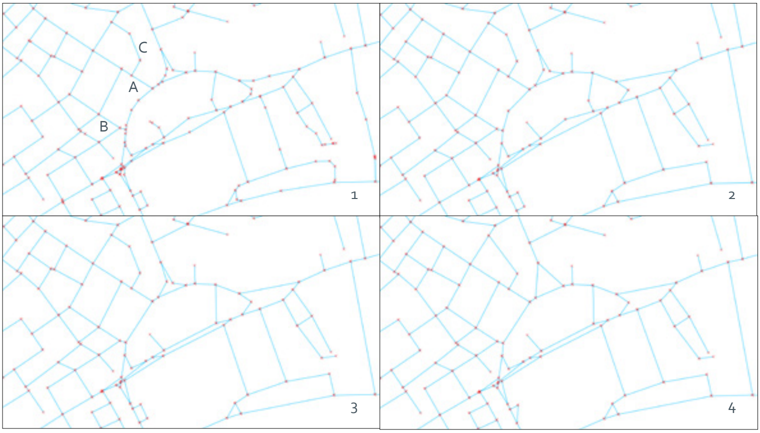

Figure 4 - Open Roads map unsimplified (1) and simplified with Douglas Peucker algorithm with tolerance 10 (2), 15 (3), 20 (4)

The result suggests that angular change calculations are optimised between continuous segments. When looking at the impact of the simplification on the structure of the RCL maps, it is obvious that their primal and dual graph shrink. The graphs become shallower, meaning that a space between two points of decision - intersections - is represented by fewer lines. This results in the increase of average angular connectivity; the nodes of the dual graph decrease but the connections between the nodes become sharper in angle.

	Primal Graph			Dual Graph			
RCL-OS	number of nodes	number of edges	total segment length (m)	number of nodes	number of edges	connectivity (average)	angular connectivity (average)
unsimplified	51,837	60,854	2,880,570.54	60,854	96,046	3.16	52.88
Douglas-Peucker 10	34,571	43,493	2,868,190.09	43,493	78,363	3.60	61.87
Douglas-Peucker 15	32,639	41,495	2,855,497.07	41,495	76,154	3.67	62.33
Douglas-Peucker 20	31,352	40,122	2,838,266.29	40,122	74,507	3.71	62.43

Table 2 - Changes in size and properties of the primal and dual graphs of unsimplified and simplified RCL maps (Open Roads)

RCL-OS	Primal Graph			Dual Graph			
	number of nodes	number of edges	total segment length (m)	number of nodes	number of edges	connectivity (average)	angular connectivity (average)
unsimplified	173,469	194,445	4,330,880.0	194,445	280,616	2.89	45.83
Douglas-Peucker 10	75,533	95,728	4,283,746.1	95,728	180,904	3.78	62.94
Douglas-Peucker 15	73,133	95,752	4,251,204.1	95,752	190,565	3.93	63.22
Douglas-Peucker 20	69,336	89,785	4,228,202.3	89,785	174,143	3.88	63.31

Table 3 - Changes in size and properties of the primal and dual graphs of unsimplified and simplified RCL maps (OSM)

The Douglas-Peucker generalisation seems to make a better proxy of the human cognitive wayfinding behaviour regarding the perception in change of direction of a person moving from one segment to another and how a person perceives a space to be continuous. The correlation coefficients between angular choice values of linked axial and Open Roads map and OSM map support this idea. The values of the simplified maps are closer than the ones of the unsimplified maps.

When looking at the percentage change of the correlation (table 3) the simplified maps improve greater at local scales where the gap between values of the axial and the unsimplified RCL maps was bigger anyway as shown in the previous experiment. However, at local radii the maps are still quite different. At city-scale scales of 3,200 meter or more axial and RCL choice values are closer. Regarding the simplification tolerance, the improvements are minor when increasing the threshold from 10 to 15 or to 20. Moreover, it seems that the simplification algorithm can address the sensitivity of the analysis to the over-representation of space in OSM by improving the correlation up to 40% in comparison with the unsimplified OSM.

4.3 EXPERIMENT 3: AXIAL AND SIMPLIFIED RCL MAP WITH MODELLING RULES

This section focuses on the Open Roads RCL map, which in the previous experiment had a better correlation with axial segment analysis. The Open Roads map from the previous experiment, already simplified with the Douglas-Peucker algorithm, is being further simplified in this experiment with modelling rules of special spatial cases typically found in a city's grid. These rules have been set in section 3 and have been applied manually to the model as they yet lack efficient simplification algorithms.

The modelling rules applied at roundabouts, staggered junctions, squares, underpasses, overpasses, bridges and parallel lanes all aim at reducing the number of nodes in a dual graph representation of the RCL map (figure 5). Geometrically speaking, when moving from intersection A to intersection B if no other point of decision of direction is involved in one's movement, a segment is drawn as a straight link between A and B. For example, if you entering a roundabout, where multiple directions of movement cross there is no choice in changing the direction of your movement until you meet the next entry/exit to the roundabout. Similarly, direct connections are drawn in open convex spaces where there can be uninterrupted movement and clear visibility between the surrounding junctions of a square. The angular deviation of trips between all possible entry and exit points of the square is optimised with a direct straight link. Although the rule of staggered junctions might conflict with the attempt to decrease depth in a RCL map it seems to account for slight changes of angle between almost continuous segments.

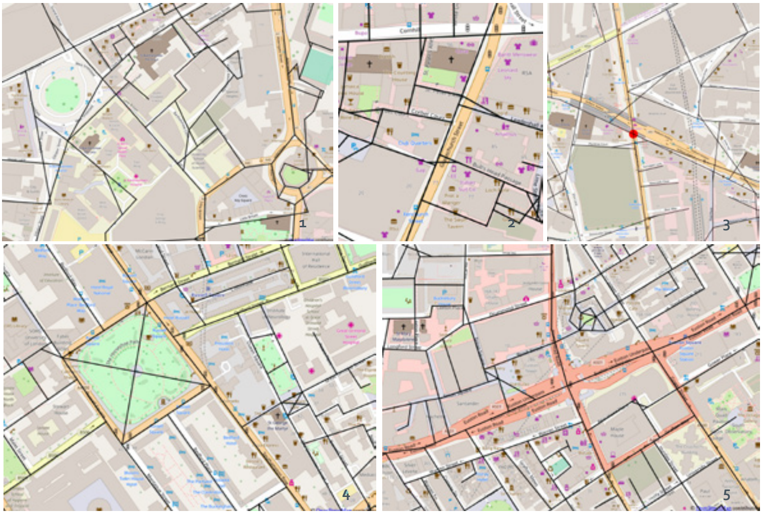

Figure 5 - Example of suggested modelling rules in London map (1) roundabouts, (2) staggered junction, (3) overpass, (4) squares and (5) multiple lanes.

The values of Spearman's rank correlation between the hybrid map and the axial map show great improvement at local scales from 800 m. to 2000 m. (table 3). However, at bigger scales of analysis there is a slight negative impact on the correlation. Naturally local analysis of street network configuration improves when local conditions are taken into account, but this is not necessary beneficial for larger scales of analysis.

The above findings imply that when analysing the angular configuration of urban systems at local scales, where trips are no further than 2000 metres, a necessary process of validation must be conducted by the analyst. This may involve drawing additional segments, deleting connections that may no longer exist and optimising angular changes between routes in the maps. This process of validation can be achieved by overlaying maps from web mapping services such as Google maps, OpenStreetMap etc. However a site visit is recommended.

	OS Open Roads				
	unsimplified	**simplified** (Douglas-Peucker 10)	**simplified** (Douglas-Peucker 15)	**simplified** (Douglas-Peucker 20)	**simplified** (Douglas-Peucker & modelling rules)
choice800	0.5673	0.598	0.6063	0.6113	0.638
choice1200	0.62	0.6454	0.6545	0.6586	0.6718
choice2000	0.6698	0.6872	0.697	0.7014	0.7055
choice3200	0.6997	0.7094	0.7194	0.7242	0.7173
choice5000	0.7075	0.7165	0.7267	0.7313	0.7149
choicen	0.6704	0.6867	0.6964	0.701	0.6839

	OpenStreetMap			
	unsimplified	**simplified** (Douglas-Peucker 10)	**simplified** (Douglas-Peucker 15)	**simplified** (Douglas-Peucker 20)
choice800	0.4129	0.4506	0.4618	0.4634
choice1200	0.4622	0.5	0.5083	0.5129
choice2000	0.509	0.5448	0.5493	0.5584
choice3200	0.5282	0.5641	0.5676	0.5784
choice5000	0.5322	0.5685	0.5714	0.5829
choicen	0.4952	0.5415	0.5402	0.555

	OS Open Roads			
	simplified (Douglas-Peucker 10)	**simplified** (Douglas-Peucker 15)	**simplified** (Douglas-Peucker 20)	**simplified** (Douglas-Peucker & modelling rules)
choice800	5.41%	6.87%	7.76%	12.46%
choice1200	4.10%	5.56%	6.23%	8.35%
choice2000	2.60%	4.06%	4.72%	5.33%
choice3200	1.39%	2.82%	3.50%	2.52%
choice5000	1.27%	2.71%	3.36%	1.05%
choicen	2.43%	3.88%	4.56%	2.01%

	OpenStreetMap		
	simplified (Douglas-Peucker 10)	**simplified** (Douglas-Peucker 15)	**simplified** (Douglas-Peucker 20)
choice800	9.13%	11.84%	12.23%
choice1200	21.09%	23.10%	24.22%
choice2000	31.94%	33.03%	35.24%
choice3200	36.62%	37.47%	40.08%
choice5000	37.68%	38.39%	41.17%
choicen	31.15%	30.83%	34.42%

Table 4 - Spearman's rank correlation coefficient between angular choice values of unsimplified and simplified RCL maps and axial map (left). % difference in Spearman's rank correlation between unsimplified RCL maps and simplified RCL maps (right).

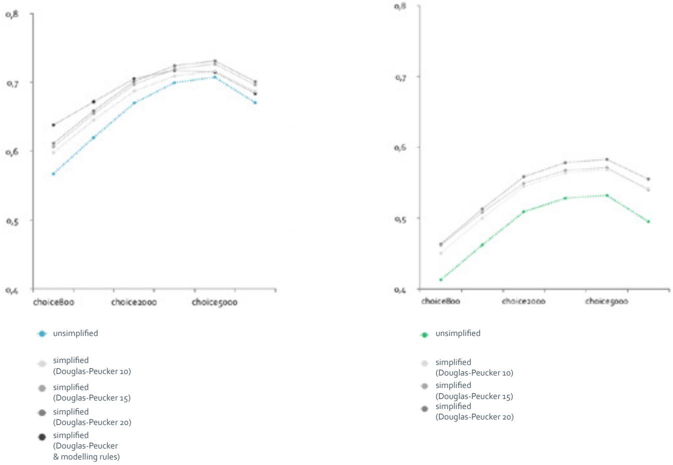

Figure 6 - Changes in the Spearman's correlation across different scales of angular segment analysis for axial and Open Roads maps (left) and axial and OSM map(right)

5. DISCUSSION

Gathering the results of our analysis, we will make an attempt to formulate the simplification processes for RCL maps prior to angular segment analysis. The suggestions made here should be further tested and validated. The principles on which the rules are based are the optimisation of angular change between continuous intersections and the reduction of nodes, provided that connections are not distorted.

Sequence	Operation
1	selecting only lines of the network that correspond to the pedestrian/ vehicular or any other mode of movement the analyst is interested in
2	removing invalid geometries (including points)
3	removing duplicate geometries
4	removing overlapping geometries
5	breaking geometries where they share vertices; geometries should not be broken where they cross but not intersect as these crossing points in a RCL map are the equivalent of unlinks in an axial map
6	segmenting
7	snapping geometries
8	simplifying with Douglas-Peucker algorithm

Table 5 - General simplification operations and algorithms to apply prior to the analysis of a RCL map.

The operations and algorithms in table 4 are suggested to be used when the analyst's focus is primarily at large scales over 2,000 m. When the analyst is looking at a local radius then it is suggested that the RCL map should be further simplified using the modelling rules covered in section 3.4. These modelling rules are based on two principles: the minimisation of nodes representing a space and the optimisation of angular change. For example, it is still valid to create additional nodes if a route cannot be optimised otherwise (figure 7). But it is not necessary to add an additional segment that already represent a connection with a similar angle. This process of simplification might be a very time consuming task however it is necessary if one wants to look at how angular changes may affect local patterns of activity.

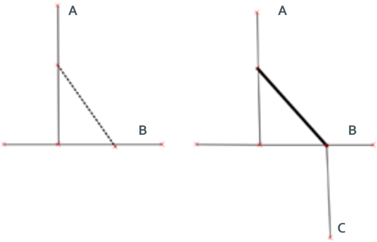

Figure 7 - The dashed line does not minimise the angle between segment A and B and thus it is not necessary (left). The highlighted line is not necessary to minimise the angle from A to B but is necessary to minimise the angle of A and C (right)

To generalise these rules further, experiments should be conducted with different map sizes, maps from different cities with different complexities in their geometry and maps from different data sources. Moreover, to create a better specification of the modelling rules, separate tests on each rule would help us understand the effect of individual changes on the analysis outcome. Stronger arguments need yet to be developed explaining why these modelling rules are improving the results of the analysis.

It is also important to note that all four maps used in this study are maps with different levels of resolution, of different years and from different sources. Therefore, there are cases where one street may appear in one map and not the other. This may explain partly the low correlation coefficient in local radii. The aim of this study was not to achieve a high correlation between analyses of axial and RCL maps but to explore how their correlation changes when maps are simplified.

Methodological limitations of this research also include the linking of axial and RCL maps, where in complex cases the links may fail to link segments correctly. Processing time limitations have discouraged us from using larger models of London and cast doubts on the correlations at radius N, which therefore has not been commented on so far. Opportunities for future development of this methodology lie also in the integration of other datasets or properties of the networks. Open Roads for example includes information on type of a line such as 'roundabout' or 'sliproad', which could be useful if simplification processes were to be automated. This is an approach taken by the sDNA software when using RCL maps from OS ITN (the most detailed commercial RCL data sets of the UK). Additional datasets could also help cases such as open spaces and parks. Cases that involve level differences (stairs, lifts etc.) would require much more extended research.

These results are preliminary and there is a lot more to be explored. However it is important to highlight that if you think of the number of lines of a city-scale map, it is inevitable to simplify all

geometric cases. There will always be unique and complex cases. Even attempts to automate the creation of the axial map itself "have highlighted the fundamental inconsistencies of any representation" (Turner, 2005). The simplification algorithms and rules are explored with the purpose to approach an axial map analysis. The axial representation is "an approximation to the underlying nature of space [as understood by the occupant]" (Hillier 2003 in Turner 2005) itself and the simplification of RCL maps is used as another proxy for that.

6. CONCLUSION

The main objective of this study was to show how the simplification of RCL street network representation can enhance the accuracy of the analysis. Our three experiments have indicated that if RCL segments are simplified their analyses can come closer to an axial segment analysis. However, different rules apply to different depths of analysis. Analysts should always be very cautious of what simplification they apply according to the question they are looking to answer. When the focus is on city-wide radii, general simplification rules seem to be enough to push the results closer to an axial map, but when the emphasis is placed on local radii a process of validation and optimisation is required to improve the results of the analysis.

The theoretical underpinnings of how a RCL segment represents space have only slightly been discussed in this paper. The principles suggested are derived from the definition of axial maps as the longest and fewest lines and are specific to the choice segment analysis that uses the shortest angular path algorithm. Minimisation of node count is achieved by removing redundant segments that involve minor angular changes in a nevertheless continuously visible and accessible space, while at the same time nodes are introduced where there is a potential of optimisation of angular change.

The authors' intention is to continue research on optimal algorithms for simplifying RCL maps by attempting to introduce generalised rules and case-specific simplification algorithms. We hope techniques to evolve that will help analysts apply space syntax analysis in a consistent and rigorous way.

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ASSISTED AGENT-BASED SIMULATIONS:

Fusing Non-Player Character Movement With Space Syntax

PETROS KOUTSOLAMPROS
Space Syntax Laboratory, University College London, London, United Kingdom
petros.koutsolampros.11@ucl.ac.uk

TASOS VAROUDIS
Space Syntax Laboratory, University College London, London, United Kingdom
t.varoudis@ucl.ac.uk

ABSTRACT

Agent-based simulation is one of the core tools of spatial analysis utilised to provide an understanding of space when complex parameters come into play, such as how the visible space changes while traversing a building, or what happens when there is a destination to be reached.

This type of simulation has a lot in common with techniques used in video games to create movement trajectories for non-player characters. Although these techniques have been developed over the years to provide more realistic and more "human-like" behaviour, they are rarely woven back into analytical and simulation tools. As a first step to remedy that, we developed a new methodology that fuses non-player character movement from computer games with simulation techniques traditionally used for agent-based analysis in Space Syntax. This first attempt utilises a different type of underlying representation of space, known as a navigation mesh.

We first examine in detail two traditional techniques utilised in depthmapX agent-based analysis and highlight their strengths and limitations. We then describe how this technique differs from the classic space syntax methods, as well as how it can be combined to create hybrid analytical models of movement. The hybrid model developed in this case is that of a classic space syntax agent assisted by the aforementioned technique. We then tested and evaluated the traditional and new models for their capacity to explore two gallery spaces.

The results extracted from the new hybrid simulation model depict agents with more capacity to explore, a significant addition to the traditional space syntax agent based methods.

KEYWORDS

Space syntax, agent-based simulation, navigation mesh

1. INTRODUCTION

Within the field of Space syntax agent-based models have been employed to provide a stochastic alternative to the deterministic Visibility Graph Analysis, to study how human movement can be approximated, and to act as an alternative evaluation tool to observations for understanding the relationship of movement to the various metrics that describe space. An agent-based model is an example of a simulation in which autonomous agents are left to wander a virtual space having only a small set of simple rules to follow. Through this set of rules and the interactions

between the agents a complex system emerges. Batty (2001) specifically highlighted agent-based models as alternatives to large aggregative models which are built from the top down.

In parallel, video games have been utilising agent-simulation as a way to allow non-player characters to move through the virtual game world, and thus provide interactivity to the narrative of the medium. A common method used to allow for this kind of movement is path-finding through a navigation mesh. A navigation mesh is an underlying (non-visible to the player) representation of the 'walkable' space in the game world, and it is comprised of a set of convex polygons that are inter-connected. As mentioned by Snook (2000), its main purpose is to allow for a crude approximation of the virtual world which can in turn be used to calculate paths quickly. He states that "the added bonus is that our replacement for the 2D grid can have cells of irregular shape and size, wind up and down stairs and hills and even overlap itself on things like bridges and catwalks". While this approach is especially beneficial as a 3D representation, the majority of the Space Syntax research focuses on two dimensions and thus we only utilise 2D instances.

In the next two sections we examine the development and general background of the two representations, as well as how they are used today. The next section describes agent-based analysis in general and where the direction decision making process happens, while the two after that examine the two Space Syntax 'look' methods, and the new suggested 'look' respectively. Section number seven describes the method of evaluation for the three techniques as well as the results of this evaluation and the last section discusses the results and provides possible directions for future research.

2. BACKGROUND: AGENT-BASED RESEARCH WITHIN SPACE SYNTAX

The Space Syntax field had a long history before agent analysis was introduced, with roots at Hillier and Hanson's 'The social logic of space' (1984) which considered the elements of space (rooms, lines of sight) as parts of a graph, an abstraction that allowed mapping on it different concepts such as social and physical behaviour. This abstraction was combined with Gibson's theory of affordances (1986) and Benedikt's isovists (1979) to create what is known today as Visibility Graph Analysis (VGA). VGA is a framework that allows the analysis space by dividing it into cells and connecting these cells in a graph if they are inter-visible. VGA is deterministic, in that the same spatial configuration will always produce the same result.

Turner and Penn (2002) identified the need for a model of human movement that does not follow a grand theory about the underlying space, but which regards "the environment as the provider of possibilities rather than a place to be rationalised" (Turner and Penn 2002, p.473) and set out to identify whether it is possible, and to what extend, to use configuration to explain movement by using one such model. The authors suggested that other examples of agent-based models which depended purely on the physical displacement of humans (Helbing and Molnar 1998) or those that treated the problem as one of least-cost paths (Hoogendoorn et al. 2002) created agents that lacked a basic driver for natural movement, the ability to see.

Turner and Penn considered this an omission and created an example of agent-based analysis that incorporated this ability. They initially followed a specific idea, that when engaging in natural movement, a human will move towards further available space as determined by his or her current visual field. The researchers thus developed a model with an agent that had a specific visual field which in its turn depends on an EVA (Exosomatic Visual Architecture), in this case a Visibility Graph as those suggested by Turner et al. (2001). The underlying graph had a 0.75 x 0.75 m resolution grid to approximate the average human step length: 0.77m (Sutherland et al. 1994). The EVA allowed the agents to pick a location out of the ones in their visual field, take a step towards that location, change direction and repeat. The implementation favoured the availability of space, thus the agents were more likely to turn and walk towards the areas within their visual field that had more space. The algorithm that made this selection will be referred in this paper as the 'standard look".

The original implementation introduced some limitations to account for the corporeal nature of human beings, i.e. it did not allow two agents to be on the same cell of the graph, or walk or see through walls. These limitations introduced possible gridlocks where the agent had no available space in the visual field. In this case the visual field of the agent was expanded to 360° and a new pixel was chosen through the whole isovist. Turner and Penn proceeded to test this new method against observed movement captured earlier (Turner and Penn 1999) with the aim of finding the combination between number of steps and field of view that had the best correlation with the observed data. The combination that best correlated with human movement was found to be 3 steps before a change of direction and a field of view of 170 degrees. Turner and Penn also tested an implementation of the algorithm that chose directions at random but found that it did not correlate well with the observed data.

In a later study (Turner and Penn 2007) the authors suggested that an agent following a natural movement schema may opt to follow specific paths that open new possibilities for exploration . In order to encode this type of affordance into their model, the researchers extended the agents' available input to include line-of-sight (LoS) information. The agents could thus identify, within their immediate environment, in what direction they could see further and choose to turn and walk in that direction. This algorithm will be referred in the rest of this paper as 'LoS look'.

Both methods were tested for correlation against data collected through observation in the Tate Britain Gallery in London. Both the 'standard look' and the 'LoS look' were found to correlate well with the observed data with coefficients (R2) of 0.79 and 0.78 respectively for 3-step movement. Turner and Penn also calculated two extra measures, the 'total coverage of rooms' which were visited by at least one agent and the 'per-agent cumulative isovist', the mean fraction of building area that could have been viewed by an agent during its visit, had it had 360 degree vision. They suggested that the cumulative isovist gave an idea about how optimised an agent is in terms of explorative ability.

In a study by Penn and Turner (2001) a similar agent model was tested, only this time the agents had access to the 'clustering coefficient' metric of the underlying visibility graph. This provided them with a way to distinguish junctions in the space and move towards them. The new model was tested, along with the 'standard look' one, against observed trails in a department store. The 'standard look' model outperformed the new model most likely due to the fact that the next random step is chosen from the field of view and is thus more likely to stay along long lines of sight.

Most of these models have been tested on exhibition or retail spaces for which the words of Gibson properly describe human behaviour: "When no constraints are put on the visual system, we look around, walk up to something interesting and move around it so as to see it from all sides, and go from one vista to another. That is natural vision…" (Gibson 1986, p.1). Some studies provided the agents with the knowledge of origins and destinations to simulate this effect.

Ferguson et al. (2012) reported two limitations with previous models. The original EVA models used the amount of visible space in front of the agent to determine the next destination and would change direction every three steps. The agents in this model would therefore favour big open spaces simply because an agent standing at the edge of such a space would have the biggest amount of visible space toward the centre. A change to the model suggested by Turner (2004) partially solved that problem by requiring the agents to reach a visible destination before changing direction, but since open spaces are a large percentage of all spaces in a building most destinations would still be in them. Therefore Ferguson et al. (2012) suggested to complement the EVA model with a second lookup table of origins and destinations that reflect each activities at those locations. An agent can then use this information to choose a direction based on how closer it takes him or her to the assigned destination, making this destination a form of attractor.

Implementation of many of the above mentioned methods can currently be found in an open source software tool called depthmapX (Varoudis 2012). This tool is currently used by the Space Syntax community to carry out agent analysis and encapsulates many of the ideas for this and other types of analysis. The original implementation was developed within UCL by Turner (2007) and was eventually re-engineered and open sourced by Varoudis (2012).

3. BACKGROUND: VIDEO GAME PATHFINDING AND NAVIGATION MESHES

Like the above-highlighted research, video game development required ways to interact with virtual space. Especially with the advent of three-dimensional computer graphics, space became the primary environment a player navigates, and in order to build believable stories non-player characters were eventually introduced. For the stories to be immersive, video games also required these characters to move naturally so that they can lead players through a space, or act against them. In contrast to research though, video games required this to happen in real time and could not depend on grid-based solutions like the ones developed in the field of Space Syntax. Therefore, other solutions were developed that were more lightweight and provided good approximations of natural movement.

One of these solutions was a navigation mesh (Figure 1, left). First mentioned by Snook (2000) a navigation mesh is a set of convex polygons that signifies the space an agent might walk on. Snook specifically suggested this as a way to provide a crude representation of a 'walkable' area, which is not as detailed as the virtual world and can be used to determine where an agent can walk.

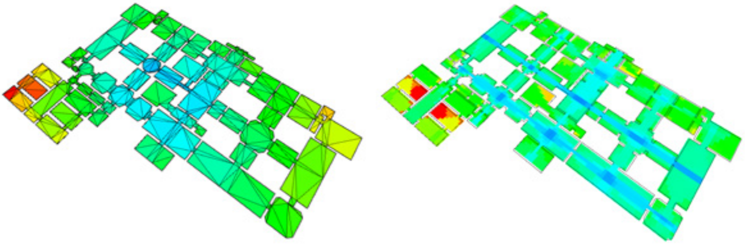

Figure 1 - Depth on a navigation mesh (left) and Visual Mean Depth on a grid (right). From deeper (segregated) areas shown in red, to shallower (integrated) shown in blue

This mesh of polygons can also be thought of as a graph. Each polygon is a node and if two are adjacent, they are connected through an edge. This allows for creation of metrics similar to VGA, such as the mean depth from any polygon to all others, which can be seen in Figure 1 (left) in comparison to the VGA Visual mean depth (right). A navigation mesh also acts as an EVA for non-player characters to utilise, traditionally a path-finding method. The underlying traversal algorithm, typically A* (Hart et al. 1968), is used to identify a series of consecutive polygons (nodes) to go through in order for the agent to reach another area in the map. Another algorithm then provides an actual line-path through these polygons, such as a 'Funnel algorithm'. Cui and Shi (2012) provide an example that describes the whole process. In their simplest implementations most of these algorithms create paths that join the centres of polygons, or the midpoints of the edges.

The lack of regularity of the polygons in a navigation mesh provides specific strengths and weaknesses. It allows us to describe the space in more detail, for example it is much easier to determine where an opening is, given that its vertices are used to generate the mesh. The previously mentioned grid representation suffers from two related problems. If a small cell size is chosen that provides a lot of detail, analysing that grid will require a lot of computational power due to the sheer number of cells. If that is not available, then a larger cell size can be selected which will require less computational power but will also provide less detail, and thus more potential for error. On the other hand, the perfect regularity of the grid allows for much cleaner analysis, since all the elements are the same, while analysis of a navigation mesh will need to control for their size and shape.

4. AGENT-BASED ANALYSIS: OVERVIEW

Agent-based analysis in the Space Syntax field is currently done using the software tool depthmapX (Varoudis 2012), although for this study we duplicated the algorithms in a different application that allows for more flexibility in the display of the metrics. The simulation is typically run with a large number of 'agents' that perform a specific process. Each agent is given a certain field of visibility and is left to roam a space for a specific amount of time. Roaming involves the agent deciding a direction, 'walking' in that direction by taking a predefined number of steps and then repeating the process.

Responsible for choosing a direction is a 'look' algorithm. This algorithm takes the agent's position, orientation and environment (EVA) into account and decides what the new direction should be. The agent's visibility system uses a set of 32 'bins', a radial assortment of the pixels around a specific cell according to the angle they are found, as seen in Figure 2. The look algorithm selects a bin and a random direction within that bin to 'step' towards. The various look algorithms help choose the bin by weighting each one of them according to different parameters. This study is interested in the direction decision-making process and thus all other parameters are kept the same throughout all tests.

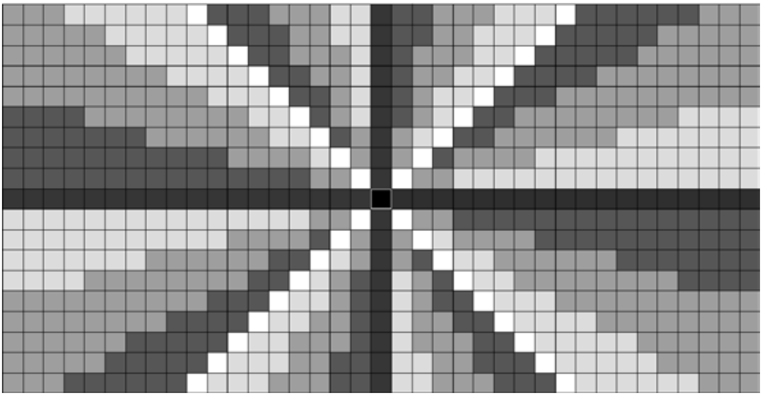

Figure 2 - Cells around a central cell (black) grouped in bins. Adjacent bins in different shades of grey. Counter-clockwise in top-right quadrant, bins: 32 (horizontal left), 1, 2, 3, 4 (top-right diagonal), 5, 6, 7, 8 (vertical top).

5. REVIEW OF EXISTING 'LOOK' METHODS

This section will focus on the two 'look' methods already mentioned in the literature 'standard' and 'LoS'. As we described above, each method utilises the underlying EVA to make a decision about which bins to favour more out of the 32 available.

5.1 STANDARD LOOK

In the 'standard look' (Turner and Penn 2002) algorithm (Figure 3) before every step a pool of choices is created that contains as many bin choices, as there are cells within that bin. A selection is made at random from this pool that indicates which direction to follow. The bins that contain many cells are thus more likely to be selected given that they were placed in the pool more times. This has the effect of driving the agents towards the largest spaces within their visibility field.

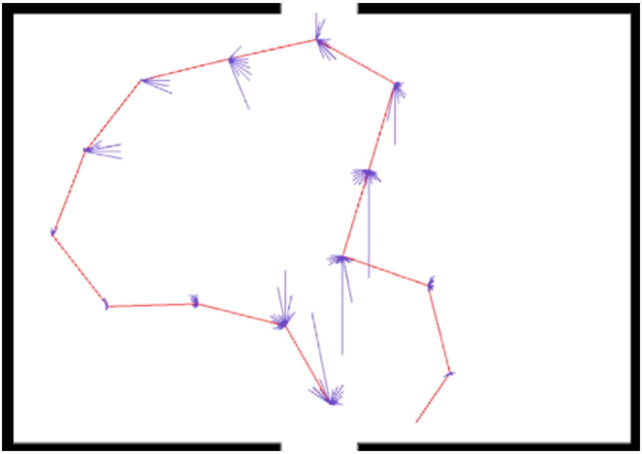

Figure 3 - The path (in red) of a single agent utilising 'standard look' bin weighting in a room with two doors. Decision points noted as radial sets of blue lines representing each bin and each line's length the weight given by the algorithm to that specific bin

The effect of this look technique can be seen at Figure 4. As expected, cells that are close to the walls point towards the centre of the room, while ones closer to the centre have an effect that spreads in all directions. The existence of an opening in this case that leads to more space beyond eventually pulls the relevant bins in that direction. In Figure 4 (right) we can see that this algorithm suffers from a low resolution in the underlying grid. Directions that are equidistant to the walls can have very different multipliers due to the underlying representation.

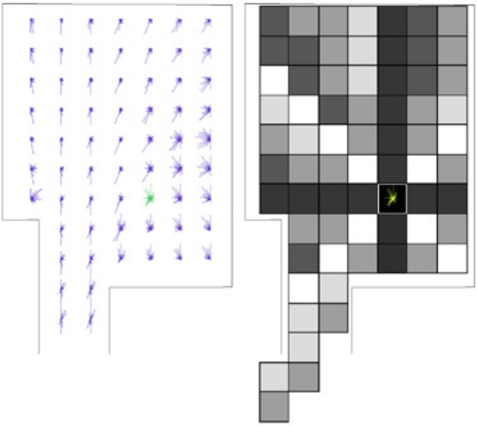

Figure 4 - 'Standard look' at all positions (left) and visualisation of bins for a specific point (right)

5.2 LINE OF SIGHT LOOK

The LOS (Turner and Penn 2007) algorithm on the other hand weighs the bins according to the maximum distance visible from within the bin. This distance is calculated by taking the distance of the cell the agent is on to the cell that is furthest away from it within each bin. The bin selection process is the same as the one for the 'standard look' but in this case the algorithm makes the bins that have cells furthest away more likely to be selected.

The overall effect can be seen in Figure 5. Once again, the cells that are closer to the wall tend to have bins that point toward the centre, while cells that approach the centre tend to have more distributed bin weighting. In contrast to the 'standard look' algorithm the 'LoS look' algorithm does not suffer from low resolution as much, although it can still skew the results dramatically as soon as new pixels are visible.

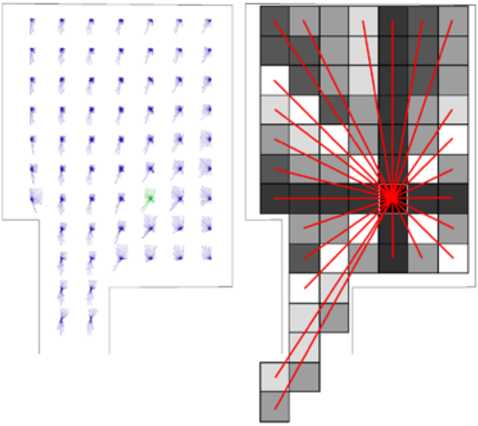

Figure 5 - Line of Sight (LoS) look at all positions (left) and visualisation of bins and distances from a specific point (right)

6. UTILISING THE NAVIGATION MESH IN DECIDING A DIRECTION

One of the core features of the Navigation Mesh is that it can describe the surroundings of the virtual world in terms of convex polygons. This allows us to find whether a specific triangle side belongs to a wall (not connected to another triangle), is part of the room (connected to another fully visible triangle) or a passage (connected to a non-fully-visible triangle). Using this categorisation we can identify where a specific agent may enter another room. This information can act as an intermediary step to the previously mentioned 'look' methods. It is information local to the room which points to possible ways out but deals with the actual visible surface instead of the amount of space or longest line of sight. Knowledge of this information (doors or 'gates' between spaces) can act as another 'affordance' used to navigate, as the ones described by Gibson(1977). The navigation mesh representation is not discrete (does not use a grid) but each point lies on continuous space.

6.1 ASSISTED STANDARD LOOK

The weighing is based on the angle a bin has from a specific point. If there are multiple passages then all of them contribute to the weighting. Given that this representation is continuous we found it fitting to use a continuous method of weighting to also avoid the pitfalls of discretisation such as slight inaccuracies or problems created from low resolution.

Specifically, a bin is weighted more heavily if a radial line starting from the cell the agent is standing on and passing through the middle of the bin is at a closer angle to the line with the same starting point, but an ending at the middle of the passage. The power of the effect is linear (a bin at twice the angle from the passage will gain half the weighting), but any other function could be used to achieve more or less focus towards a passage.

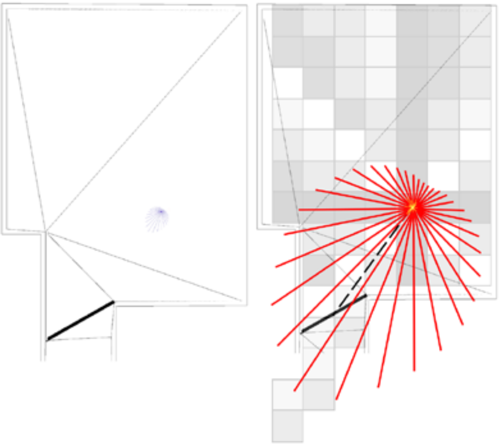

Figure 6 - Passage (heavy black line, left) and effect on each bin (right)

Instead of applying this weighting on its own we tested a fused methodology which takes into account both the 'standard look' weighting and the one described above. We will refer to this approach as 'assisted standard look'. Like the 'standard look' algorithm, each bin is added to a selection pool as many times as it has cells, but this time for each bin this number is multiplied by the weighting. Therefore, in a single-passage example bins that are almost perpendicular to the door will keep about the same weight, the ones that point towards the passage will have their weight increased while the ones that point away from the door will have their weight decreased. The effect is shown more clearly in Figure 7 where the 'standard look' in the previously shown room is affected. The overall effect of the room remains (pull to the centre) but the bins that point to the door are now more heavily weighted.

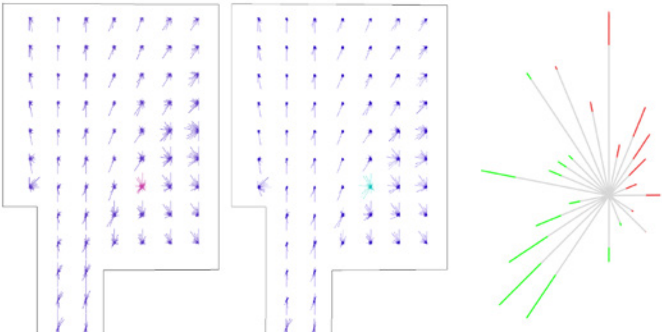

Figure 7 - 'Standard look' (left), effect of angle-to-passage on 'standard look' (centre), and closer inspection of the effect (right) with positive effect (lines made longer, green) and negative effect (lines made shorter, red)

This hybrid look algorithm allows the passage to function like a local attractor no matter how much empty space there is behind it. It can therefore specifically address what Turner and Penn (2002) identified as a possible limitation of the methods that use line-of-sight or walkable surface as affordances: "Our model uses infinite sight, and therefore an infinitely long corridor with respect to side corridors would drive all movement continuously along that corridor, whereas we might expect a human to take an exit some way along the corridor" (Turner and Penn 2002, p.481)

7. EVALUATION: AIMING FOR EXPLORATION

In order to build some preliminary confidence about the new methodology we developed two new visual-agent metrics to measure the success of the algorithm, the speed of exploration and the percentage of stuck steps. In the first case we defined an agent as successful if they managed to explore a large amount of space, much like Turner and Penn's (2002) per-agent cumulative isovist. The metric is specifically defined as the number of unique cells 'seen', that is, new cells that appeared within an agent's visual field as they took a new step, divided by the number of steps taken.

We tested four implementations, the standard look, LoS, assisted standard and assisted standard with power of effect at 2, across two buildings, the National Gallery and the Tate Britain Gallery both in London. The field of view and number of steps of the agents before a new 'look' were set as in the original studies by Turner and Penn (2002; 2007) at 170° and 3 steps respectively. In contrast to the original studies, we are not comparing the agents to real people therefore we did not fully take into account the humans' corporeal nature. While the agents could still not pass or see through walls, we did not disallow them to step on a cell already occupied by another agent. Therefore this simulation can only be thought of as a test of the agents' navigating and exploring abilities and may only provide insights about human behaviour in an abstract sense.

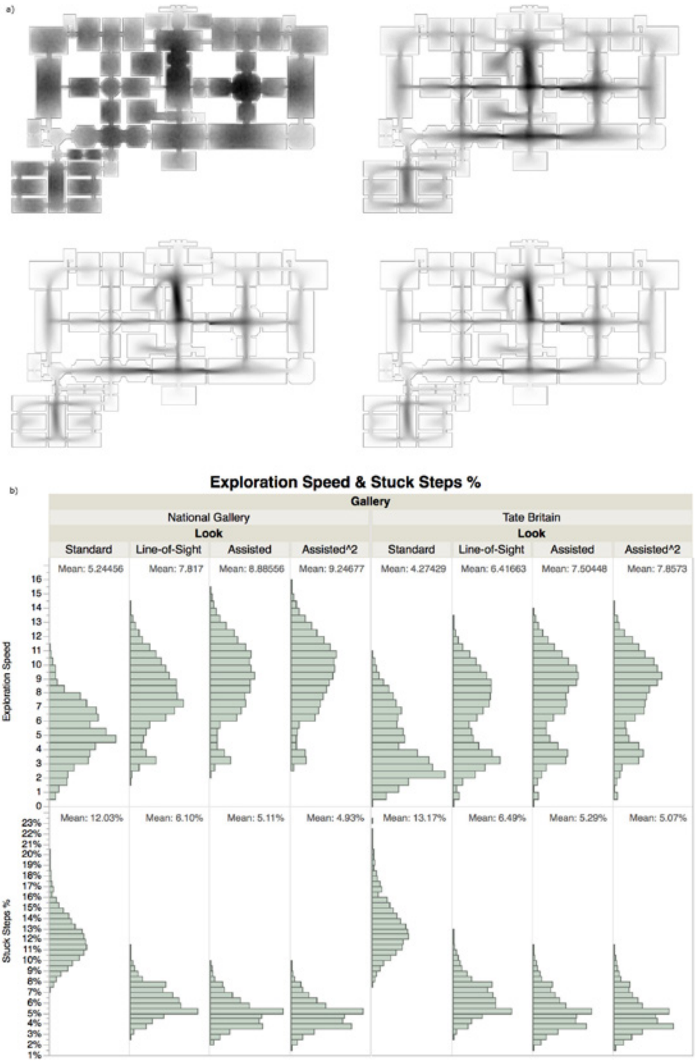

Figure 8 - a) Left to right: standard and LoS (top) portals and portals^2 (bottom) for National Gallery b) Distribution of exploration speed (top) and percentage of stuck cells (bottom) metric for the (left to right) Standard, LoS, Assisted standard, Assisted standard (2) for the National Gallery (left four) and Tate Britain (right four)

tendency for the agents to roam the same rooms or get stuck more. The other three solutions had much higher means, and smaller differences between them. It seems that 'LoS look' is indeed an effective exploration strategy, although not as effective as the new assisted standard, or the slightly more extreme assisted standard with a power of two.

The second metric examined was the number of times the agents got 'stuck' and had to open their field of view to 360° to continue. This can happen if an agent hits a wall or walks into a niche in such a way that its full field of vision is blocked and has nowhere to go. Apart from the fact that such a behaviour would be counter-intuitive for a human, it is not a strategy that optimises for exploration and thus unlikely to allow the agent to view more space. Therefore an agent and in extension the simulation that had less failed steps was deemed more successful in exploring the available environment.

The overall mean percentage of stuck steps was 7.0% for the National Gallery and 7.5% for the Tate Britain Gallery. In both galleries examined the effects are the same. Agents with the 'standard look' algorithm tended to get stuck a lot more than the LoS and the two assisted standard looks, missing on average 12% / 13% of their steps in contrast to the rest which were around 5-6%. Once again, the 'assisted standard look' algorithm (around 5%) fared slightly better than the 'LoS look' (6%), but the effect was lowest at when the power of the algorithm was increased to 2, although marginally. This effect is likely to also cause the lower values observed in the first metric. Agents that get stuck have to reset their field of vision (turn around) due to the fact that they have no available choices to walk towards, meaning that most likely for the past few steps they have been narrowing their field of view moving towards a wall or corner.

8. DISCUSSION AND FUTURE PLANS

This study was a fragment of exploratory research that aimed to understand the algorithms used for agent-based analysis within the field of Space Syntax and identify potential ways to expand them, taking into consideration the advances in computer-games research. Relevant developments in video game research were discussed that offer new perspectives to the overarching aim, to simulate natural human movement. We presented an evolution of the Space Syntax methods with techniques from these new perspectives in the form of an 'assisted standard look' algorithm.

We examined and described the inner details of two traditional algorithms described by Turner and Penn (2002; 2007), highlighted their potential and limitations and provided possible ways to introduce novel methods from video game research. We used an underlying navigation mesh representation to allow for the identification of passages when an agent is located in a room, and a new, hybrid look algorithm that affects the 'standard look' with an angle-to-passage weighting.

We then presented a new algorithmic methodology tied specifically to a task -to explore more space- and tested the various 'look' methods against it. We found that while the results are not extremely different between the various look algorithms, we could observe substantial differences, especially between the 'standard look' algorithm and the rest. The differences identified were that agents with the 'assisted standard look' tended to explore more cells, and get stuck less than the ones with the traditional algorithms. This reminding us more the feeling humans have while exploring new, never seen before, topo-geometric layouts and constantly looking for the thresholds to new areas for exploration.

On the other hand, the similarity of the results when using the new algorithm and LOS does not clearly point to one of them as the best. If the discussed methods of evaluation are to be used in a different analysis, the choice of algorithm may need to come down to other factors, such as the available hardware, size of the model or other data. The underlying grid used in the LOS algorithm can make calculation extremely heavy for larger models but it is a simpler representation and thus likely to be followed by other datasets. Other validation methods such as comparisons with real gate counts and movement traces will also be tested in the future to further highlight differences and similarities between these methods.

The ‘standard look’ and ‘line-of-sight look’ algorithms are just two of the many algorithms in depthmapX utilised by the Space Syntax community. In the future we plan to create detailed descriptions of these techniques to gain insights on their possibilities and limitations. We also plan to create implementations of the traditional techniques that avoid the pitfalls of the discretisation, by substituting the grid for visibility in continuous space. These implementations will then be used as bases for new hybrid techniques that take into account other elements of space such as passages, or even transparencies.

This study relied on evaluation techniques that aimed solely for exploration. This type of evaluation is useful for a specific subset of spaces (i.e. galleries) and thus more evaluation metrics need to be examined, in fields beyond Space Syntax. An example of this would be applying agent-simulation in workspaces where the staff is familiar with the space and they are more likely to aim to reach their destination (kitchens, toilets) as fast as possible. Thus, a future implementation will involve the development of techniques that allow the agents to travel through space in search of specific destinations.

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BRIDGING CONFIGURATIONAL AND URBAN TISSUE ANALYSIS

KARL S KROPF
Oxford Brookes University, Oxford, England
kkropf@brookes.ac.uk

ABSTRACT

The paper reports on theoretical research building on the work of Steadman, Marshall and others that examines in detail the basis for correlating the outputs of configurational analysis and urban tissue analysis. The aim of the research is to raise the yield of analysis when combining configurational and typo-morphological methods. A broader, overarching aim is to establish a bridge between the two different approaches to urban morphology that facilitates communication and helps to develop a more comprehensive and coherent set of concepts for understanding the structure and dynamics of the built environment.

KEYWORDS

Urban tissue, configuration, generic structure, correlation, comparison

1. INTRODUCTION AND METHODS

There is a growing body of research and practice that brings together concepts and methods from distinct approaches to urban morphology (Griffiths 2015; Lim 2015; Kropf 2009, 2014c; Marcus 2005; Osmond 2006, 2010; Oliveira 2015a, 2015b; Vialard 2015). Underpinning these efforts is an explicit or tacit acknowledgement that urban from is multi-faceted and that combining different descriptions might provide are better result than any one on its own (Kropf 2009). As argued by Bateson (1980), a strong cognitive justification for this view is the principle that operates in binocular vision to produce depth perception. The brain's comparison of two views of the same scene gives an informational yield or bonus. The quality and quantity of the yield is dependent, however, on image rectification and overcoming any correspondence problems. This raises the question, what is the basis for rectifying the descriptions generated by different methods of urban morphological analysis?

This paper reports on theoretical research that examines in detail the basis for rectifying the inputs and outputs of configurational analysis and urban tissue analysis with the aim of raising the yield when combining the two methods. The focus of the research is therefore not on identifying new measures or descriptions but the relations between established descriptive methods. The prudent conclusion is that the common element of the structured space offers a rigorous basis for rectification. It is for further research to explore more fully the more detailed relations that might realise the full potential yield of comparison.

The research has been undertaken using critical analysis and descriptive, logical-relational methods working through iterations of hypothesis, deductive analysis and inductive testing. The principal criteria for judging the results are: consistency, specificity, generality, comprehension and coherence. Important precursors to the research are set out in Kropf 2008, 2009 and 2014a. The root sources for the research include Steadman 1983 , Hillier and Hanson 1984, Hillier 1996, Caniggia and Maffei 2001, Conzen 1969, Moudon 1986, Petruccioli 2007 and Marshall 2004.

The paper will focus on results that show:

1. Primitive elements combine to form a multi-level generic structure of built form
2. Configurational and urban tissue analysis examine two distinct dimensions of that generic structure and can be clearly correlated within it
3. Distinct types of route aggregate can be identified at different levels in the generic structure
4. Route aggregates forming distinct types of sub-system correspond to the level of urban tissue in the multi-level generic structure.

In summary there is a 'structural overlap' or common element used in both configurational and urban tissue analysis. The configurational approach provides a basis for identifying types of route structure. The typo-morphological approach uses types of route structure in identifying types of urban tissue. In turn, the configurational approach undertakes measures of the route structures to establish the characteristics of different configurations. With the 'structural overlap' it is then possible to accurately combine the results of the different methods. The combination and comparison of the two provides a yield of additional information and insight that helps to improve our understanding of urban form.

2. THE FOUNDATION OF MINIMUM ELEMENTS

As in other fields of morphology, one of the starting points for achieving the aims of better communication and the growth of understanding is to identify the **minimum elements** that constitute the phenomena, expressed as generalized, abstract entities. The task is then to identify the ways in which the elements are combined to account for the diversity and complexity of specific forms.

The method of identifying the minimum elements most consistent with the morphological focus on process is to take a developmental approach. From this perspective, the question becomes, from what has built form been derived and what is the minimum set of pertinent features we need to describe the primitive elements?

The starting point is **human activity** in an **environment**.

The features of the environment pertinent to the structure of built form are essentially those of three dimensional geometry and the laws of gravity and mechanics. In terms of a geometric description of built form, the most fundamental morphological element is thus a **surface** on which activity can take place.

There are three fundamental modes of activity rooted in the human diurnal cycle and the need to move through the environment for resources:

- long distance movement
- local activity
- sleep

These modes lead to three **primitive types of surface** in terms of shape, size and relative position:

- tracks
- core territory
- shelter

A surface implies a space. At its most primitive the surface and the implied space are defined not by any constructed boundary but by the extent of an activity and any traces it might leave: footprints and the **difference** between trodden and untrodden ground.

The difference constitutes a **boundary**. However diffuse or well delineated, any distinct space must have a boundary. Spaces are **codependent** with their boundaries.

Boundaries might thus be:

- implied (corresponding to the limits of an activity taking place)
- left (traces or marks left by an activity)
- found (existing boundaries adapted for an activity)
- constructed (including as implied by boundaries of control)

Whatever the nature of the boundary, all three types of primitive bounded surface - tracks, core territory and shelter - can be considered **structured spaces** or **voids**.

Deliberately creating a boundary to form a space involves the selection, manipulation and arrangement of **materials** from the environment to create **physical structures**.

The extent to which any given type of space is defined by physical structures is variable. There is a continuum from the simple **environment**, which would be land uninhabited and unstructured by humans on the one hand and the fully **built environment** of a city on the other. In between is the **proto-built environment**, which is made up of the unconstructed, emergent forms that are implied, left and/or found and not deliberately built. Nor is it necessarily the case that all elements are defined by physical structures to the same extent at a given time. It is worth reinforcing, however, that the proto-built environment, for example prehistoric trackways, is the context in which the built environment has emerged.

When constituted by built structures, the three types of void can be referred to as:

- street spaces
- open areas (defined external spaces)
- rooms.

These terms should be interpreted as broadly as possible to allow for a wide range of specific forms. For example, street spaces include piazzas as well as urban throughways; open areas include front and back gardens as well as campus environments; rooms include habitable spaces, corridors and stairs as well as service spaces such as ducts, flues and cupboards.

Once there is an upright structure enclosing a space, an essential component for these elements to function is an **opening** to allow for movement in and out and from one to another. **Access** and **movement** are therefore fundamental to the structure of built form.

An access point establishes an **internal orientation** for a structured space which in turn forms the basis for the ways in which structured spaces can be combined.

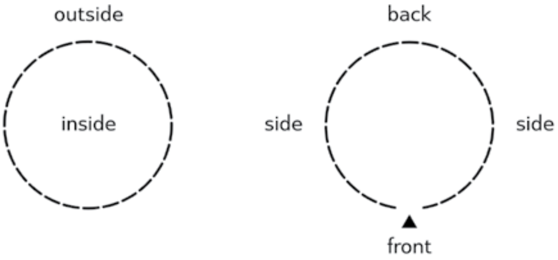


Figure 1 - Simple structured space and structured space with an opening, showing internal orientation

Colloquially, the faces established are

- front
- sides
- back.

There are also different types of opening.

- doors
- vents
- windows.

The inclusion of vents and windows adds further considerations, limits and conditions to the ways structured spaces can be combined. For the purposes of establishing the minimum elements, the only necessary type is an opening that allows physical access.

The three minimum elements of the built environment are therefore:

- surfaces
- boundaries
- openings.

The **number of openings** establishes distinct types of structured space in terms of access. At a minimum there are three access types: single, double and multiple (three or more).

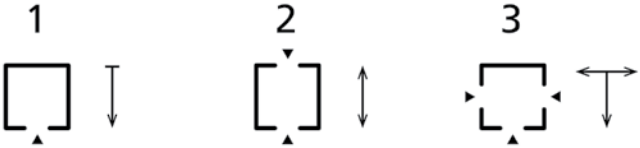


Figure 2 - Access types of structured space based on the number of openings

Each access type has a particular role within a configuration as a whole in terms of the potential range of generic functions it can accommodate.

- Occupation
- Through movement
- Distribution.

These are, of course, not mutually exclusive. Above a minimum size, all spaces can be used for occupation and also accommodate local movement. Distribution is a subset of through movement that allows for greater **choice**. The three access types apply to all three types of void: street spaces, open areas and rooms. The access types also form the basis for possible combinations of two or more structured spaces.

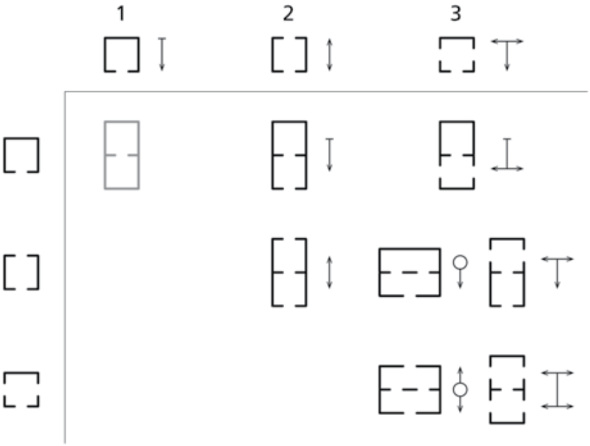


Figure 3 - Possible combinations of the three access types

The structured space diagram assumes a number of graphic conventions. The boundary represents the **plan outline** of the form on the ground plane (the reference surface). The outline assumes and refers to all the physical structures and voids within the outline in all their three dimensional detail both above and below the ground plane. Gaps in the outline and triangles represent access points.

Analytical views

The basic **outline diagram** is in effect an abstract **analytical view** that isolates the minimum elements of surface, boundary and opening. Because the diagram abstracts and combines only the three minimum elements it can be used to represent all different kinds of simple and complex structured space.

An important consequence of using the outline diagram to render all three types of void is that all parts of the built environment can be **positivel**y represented. That is to say, there is no 'negative' space within the built environment. A street space or open space within a plot is not leftover space between buildings but a positively structured surface. Any given surface is thus either inside or outside the built environment. Put another way, the only 'negative' spaces are those outside the built environment.

The fact that the outline diagram can be used to represent both simple and complex forms suggests that the abstract structured space is the **minimum unit of urban morphological analysis**. The three types of primitive bounded surface can be distinguished as **base structured spaces** and all, more complex forms can then be described as aggregations of the base structured spaces. Because any aggregation is in turn itself a structured space, the underlying process that leads from the base structured spaces to more complex forms can be seen as one of **recursive acts of aggregation**. The result of the process is a **compositional hierarchy of built form**, illustrated in Figure 4. as **a multi-level diagram**.

As set out in Kropf (2009), the multi-level structure necessarily involves the principle of co-extensive elements. In particular, the open areas and street spaces are co-extensive, functioning at two or more levels at once.

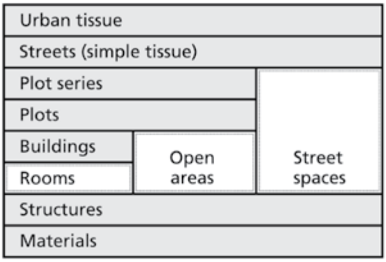
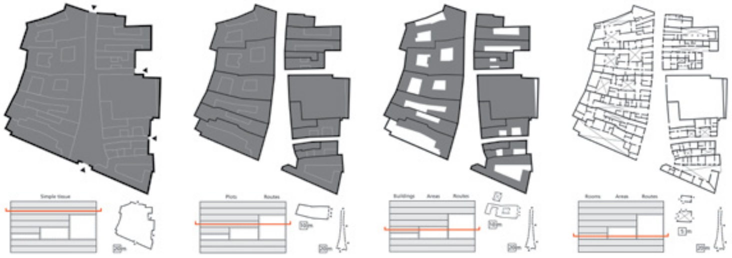


Figure 4 - The multi-level diagram representing the generic structure of built form

The compositional hierarchy represents the **generic structure of built form**. The analytical view of the multi-level diagram is in effect a kind of cross-section through the generic structure. The diagram extrudes out and exposes the different levels of order within urban tissue. The levels in the hierarchy and diagram correspond to **levels of complexity**.

A further, and likely the most familiar analytical view essential to morphological analysis is the two-dimensional **plan view**, showing the spatial arrangement or configuration of elements on the ground surface. The plan view can be presented as a composite of different elements or as a series of **element separations**. In the separations, only elements from a given level are shown, each element drawn in outline.

The element separations reinforce the idea that the compositional hierarchy represents a cross section through the generic structure of urban tissue. Each rectangle in the diagram represents all elements of a given type, represented in outline. Drawing a horizontal line through a level in the multi-level diagram 'cuts through' elements that appear in outline in the corresponding element separation. Thus, a line through the level of the plot cuts through plots and street spaces, both of which appear in outline in the plot level element separation.



a) b) c) d)

Figure 5 - Element separations with multi-level diagrams: a) simple tissue; b) plots; c) buildings; d) rooms (the Nolli Section)

In effect, the vertical and horizontal dimensions of the diagram of generic structure represent abstract 'dimensions' of configuration. In simplified terms, the vertical represents complexity and the relationship of part to whole. The horizontal represents adjacency and the relationship of part to part, which implies an abstract notion of extent. When the horizontal section is drawn at the level of the room, it cuts through all three voids in what can be termed the Nolli Section (after the 18th century surveyor who drew his famous map of Rome showing the interiors of notable public buildings, Figure 5d) . This has traditionally been the primary realm of configurational analysis – the investigation of spaces and the spatial relations between them.

One part of the foundation for the bridge between configurational and urban tissue analysis lies in the three analytical diagrams – structured space, element separation and generic structure. By using the structured space diagram to represent elements at all levels in the compositional hierarchy, it is possible to extend the methods of graph analysis as developed by Steadman, Hillier, Hanson and others to all generic types of built form. In this respect the diagram of generic structure helps to situate different methods of analysis and investigation and show their relationship to each other. Steadman's Architectural Morphology (1983) focuses on the room and building as does Hillier and Hanson's Social Logic of Space (1984). Space Syntax focuses on the route, effectively in isolation. Interestingly, the open area or plot has been the subject of very little investigation from the configurational point of view.

The perspective offered by the diagram of generic structure highlights the fact that the spatial configurations of rooms, plots and streets are constituent attributes of urban tissue. They are embedded within the vertical structure of built form. The benefit of this view is that it goes beyond the fairly obvious point that 'spaces are a part of the built environment' (setting aside the deceptively difficult task of formally defining a 'void' or absence) and identifies the specific relationships by which the voids are more easily defined.

The substance of the bridge between configurational and urban tissue analysis is the built environment itself. Our ability to cross it comes from seeing that configuration and urban tissue refer to two different 'dimensions' of the same thing.

Another part of the foundation for the bridge is the complementary relationship between configurational **types** and configurational **measures**. This distinction is rooted in the difference between quantity on the one hand and number and pattern on the other. Quantity is continuous and dimensional where number and pattern are discrete and relational. Something is 'central' only in relation to something that is peripheral but there are degrees of centrality. As emphasised by Steadman (1983), the basis for identifying configurational types is the topological characteristics of the forms – topologically distinct, discrete relationships between elements. The measures, such as depth, integration, choice etc. are used to quantitatively characterise different specific configurations. In its fullest sense, configurational analysis should seek both to identify different configurational types of pattern and compare them (or positions within them) using the quantitative measures.

3. THE BRIDGE OF ROUTE STRUCTURE

The pattern that provides what is probably the strongest and most familiar connection between configurational and urban tissue analysis is route structure.

Routes can be seen in at least three ways:

- as a movement network (infrastructure)
- as an element of urban tissue
- as a defined area of 'land use' and control

The distinction between routes as part of a network or part of urban tissue is a matter of how we choose to aggregate street spaces as one of the three types of minimum elements of urban form. There is, on the one hand the 'vertical' aggregation of elements as represented by a vertical section through the multi-level diagram of generic structure (Figure 6b). This 'embeds'

the street space into urban tissue. On the other hand, there is the 'horizontal' aggregation of spaces implied by the Nolli Section through all the three types of void (Figure 6c). The latter view is essentially to isolate the spaces, which necessarily interconnect to allow movement through the built environment. As Figure 6c shows, a network of routes can be rendered using the three access types of structured space (single, double and multiple openings, where a link is a single or double opening space and a node is a space of three or more openings.

a) b) c)

Figure 6 - a) A street space; b) the street space embedded in a simple tissue and c) an aggregate of street spaces forming a network

The approach set out below builds on the work of Steadman (1983) and Marshall (2004) by providing a basic differentiation of routes, as types, based on their position relative to other routes within the network. It is topological and discrete and works on the basic morphological principle of relative position of parts. It is possible, and desirable, to undertake the task of definition – and analysis – from both the bottom up, using the primitives of base structured spaces and the top down using the pattern of routes and settlements.

A fundamental concept for understanding the structure of longer distance route patterns is the **centre**. There are many reasons for the general pattern of nucleated and poly-centric settlements but one way or the other there is a strong tendency for the emergence of centres, that is, concentrations of activity that serve or draw on a wider **catchment**. The formation of centres pre-supposes routes to get to them and, in turn, centres can generate new routes to widen or extend access to them and increase the size of the catchment. The cumulative result is the familiar pattern in the landscape of settlements linked by roads.

To begin to articulate the pattern, it is possible to distinguish different types of route purely with reference to the position of a route in relation to centres and to other routes in the network. The first step in the analysis is therefore to identify the centres.

For the purposes of this stage of analysis, the minimum definition of a centre is any concentration of occupied buildings (departure or destination points) irrespective of use. Typically this corresponds to built up areas as identified on most maps. On this basis, a 'centre' might be a hamlet, village, market town city or metropolitan region. The principal variable to consider is the size threshold for what constitutes a 'concentration'. Depending on the scope of the study the method for establishing the threshold might be a rank-size rule or density profiling. More simply and directly the built up areas as identified on maps can be used, with smaller scale, lower resolution maps generally using a higher threshold of size for identifying settlements than larger scale, more detailed maps. In the UK, the open source Meridian 2 map set is very useful for the purpose.

Primary route types by position

However the centres are defined the first step is to **treat them as a simple structured space**, that is, in terms of the surface, boundary and access points. The next step in the process of analysis is to identify and colour code different route types based on their relation to centres.

The process of analysis necessarily disregards any existing ranking of centres or routes on the basis of designation, size, capacity etc. The aim is to identify route types **solely on their relationships to centres or to other routes**. The analysis is therefore strictly **topological**.

In essence, the first stage of the analysis is carried out at a low level of resolution, distinguishing only built up areas and the routes that are connected to but lie outside them. From this perspective there are four types of **strategic route**:

Tangential: Routes connecting several centres tangentially. The connection to the built up area is only indirect and the priority is for through traffic along the tangential route. Examples are limited access dual-carriageways, motorways and freeways/expressways.

Primary arterial: Routes connected to a centre on each end (bicentric).

Secondary arterial: Routes connected to a centre on one end and a through route on the other (monocentric).

Pericentric: Routes connected on each end to one or another of the higher level strategic route (tangential, primary or secondary).

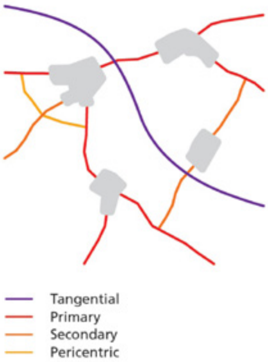


Figure 7 - Strategic route types

Once the external strategic routes have been identified, the next step is to trace the arterials into the built up areas, extending them along continuous routes (assuming forward inertia, right of way and the least angle rule) until they either end in a T-junction or emerge out another side of the built up area. Internal pericentric routes can be added after the internal arterials are identified.

Local route types by position

Working from the bottom up with the base structured spaces, the matrix of access types establishes a topological basis for identifying basic route types at the local level – that is, individual street spaces. There are four basic types of local route in terms of topological connections.

Thoroughfare: Routes connected to a different route on each end.

Through-loop: Routes connected on both ends to the same route.

End-loop: Routes connected to a route on one end and itself on the other.

Cul-de-sac: Routes connected to another on one end only.

Figure 8 - Local route types

Route structure sub-systems

Examining even a small number of places shows that these types are combined in many different ways. It is possible and not uncommon, for example, to find a loop on top of a loop and many cul-de-sacs along a cul-de-sac. It is also possible to have a grid of thoroughfares at the end of a cul-de-sac. These are sub-systems that form a distinct level of structure between the local and the global. Crucially, **sub-systems** can be outlined and rendered as a single structured space with one, two, three or more openings. There are four types of sub-system, corresponding to the four types of local route.

Thoroughfare: A set of interconnected local routes with three or more external connections to at least two different strategic routes.

Through-loop: A set of interconnected local routes with only two external connections, each to different routes, or multiple connections to a single strategic route or thoroughfare.

End-loop: A set of interconnected local routes with a single external connection.

Cul-de-sac tree: A composition of only cul-de-sacs with one external connection.

Figure 9 - Strategic routes and route sub-systems for vehicle access in central Bath. The colour coding for the sub-systems is the same as for the local types (Kropf 2014b)

The most effective and familiar method of representing the types is to colour code them using the heat map convention. In most cases it is best to code the strategic routes and whole sub-systems. Colour coding whole sub-systems necessarily ignores the type of some of the component links. The result, however, gives a clearer general picture which can be augmented if appropriate with a separate more detailed coding of individual local links.

What is of particular relevance for this paper is that route structure sub-systems also define an area that can be outlined as a structured space. Drawing a boundary around a sub-system based on its configurational type is, in effect, a first step in identifying an urban tissue. That is, if urban tissue is defined as an area of a settlement with a distinct and consistent configuration of streets, plots and buildings, the configurational type of the street pattern is one of the attributes used to identify the tissue. The constituent role of the street pattern in urban tissue is highlighted in the diagram of generic structure (see Figures 4 and 5). The street space is the 'operational void' of urban tissue that works with plot series and blocks, which themselves contain the other voids at different levels.

The two views - the part-to-whole aggregate/'vertical section' through generic structure of urban tissue and the part-to-part aggregate/'horizontal section' of route structure - are, in effect, two different views of the same thing. There is, then, a 'structural overlap' or common element used in both configurational and urban tissue analysis. The configurational approach treats route structures as aggregates of spaces and identifies configurational types of aggregate. The typo-morphological approach uses types of route structure as one element of several in identifying types of urban tissue.

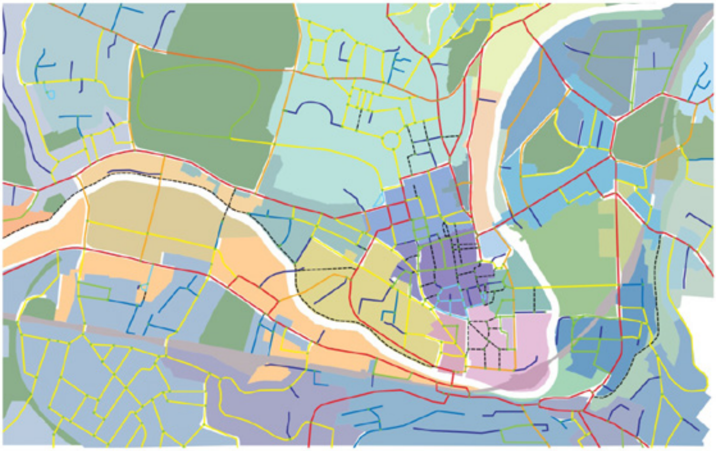


Figure 10 - Route structure types and tissue types in central Bath (Kropf 2014b)

4. CONCLUSIONS

The two approaches and their respective views are not mutually exclusive but intersecting. Most importantly, the 'structural overlap' makes it possible to accurately combine the results of different methods The same element is analysed or measured in different ways. There is an added benefit or 'yield' when the results are compared, similar to the depth perception gained with binocular vision. As shown by Bateson (1980) and Jones and Lee (1981) there is an informational and performance 'bonus' when two views of the same thing are compared in the brain. Bateson cites other examples of the same principle, which he terms 'multiple description', the essence of which is comparison. Another visual example is toggling between two images of the same view at different times. When toggled quickly enough, any change appears to the brain as motion. What is highlighted in the comparison is a relationship – 'this is in front of that' or 'there has been a change in position/time.'

Viewing types of urban tissue and configurational route types together brings out the structural depth of the area being examined in terms of: the relationships of the internal parts to the whole; the relationships between different tissues; the nature of their connections; the relationships between a given tissue and the settlement as a whole.

A further benefit of the structural overlap lies in the fact that the area of overlap – route structure – is the principal subject of the analytical methods of Space Syntax and network analysis. An additional yield can therefore be gained by combining and comparing route types with measures such as integration, choice and connectivity. Adding measures with a clear, structural point of reference adds more depth to the view and provides a foundation for making more finely tuned inferences and judgements by clearly articulating the context for the measures. When looking at the spatial distribution of such things as crime, property values or perceptual qualities it becomes possible to look at correlations with type, measures and relative position. The combination of type and measure is more powerful than either on its own.

In summary, there would seem to be at least three core benefits of combining the configurational and typo-morphological methods. 1) The configurational view adds a rigorous, topological foundation to the identification of urban tissue. 2) The sub-system types and tissues establish a more specific context for configurational measures. 3) The combination allows more nuanced and pointed comparisons and correlations and a wider range of inferences to be made. Combining methods with a common structural reference provides a yield of additional information and insight that helps to improve our understanding of urban form.

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#166

TOWARDS EMBODIED 3D ISOVISTS

Incorporating cognitively-motivated semantics of `space' and the architectural environment in 3D visibility analysis

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JAKUB KRUKAR
Institute for Geoinformatics, University of Muenster, Germany
krukar@uni-muenster.de

CARL SCHULTZ
Institute for Geoinformatics, University of Muenster, Germany
schultzc@uni-muenster.de

MEHUL BHATT
University of Bremen, Germany
bhatt@uni-bremen.de

ABSTRACT

Isovist analysis is being increasingly applied to the third dimension. However, this transition seems to be driven by a direct extrapolation of the 2D isovist concept, along with a variety of implicit assumptions that are only valid in the top-down 2D case. This results in definitions that make the 3D isovist equivalent to the geometric volume of `space' visually accessible from the generating point in the 3D building environment. Such a concept neither adequately reflects the strategy of human visuo-locomotive exploration, nor does it account for the resulting mental representation of the explored space. We review two reasons for the dissimilarity between the 2D and 3D conceptualisations of isovists:

(1) The quantity, and characteristics, of visual information relevant to the human everyday experience is different in the vertical and horizontal plane.

(2) The left/right symmetry in accessing and interpreting visual information is not comparable to the top/down asymmetry of visual information. As a result, the difference between the experience of being above an object versus being below the object is incomparable, in contrast to experiencing an object from the left side versus the right side.

Thus, a 3D isovist derived by (naively) extrapolating from its 2D counterpart limits its applicability in the studies of human cognition inside 3D environments. We propose a cognitively motivated extension of a general 3D isovist that accounts for these phenomena.

KEYWORDS

Isovist, visibility, 3D

1. INTRODUCTION

Despite being originally considered as a three-dimensional concept (Benedikt, 1979), isovists or viewsheds have typically been implemented as 2D or 2.5D computational models of visibility. Recently, there has been a growing interest in implementing isovists in the third dimension in order to more comprehensively represent visibility in buildings and outdoor landscapes. It is

now important to consider the ways in which the traditional 2D implementation is extended, and what this means to the initially conceived meaning of isovists, as well as related approaches, such as Visibility Graph Analysis (Turner, et al. 2001). Simple extrapolation of the traditional 2D methods yields a 3D isovist equivalent to the volume of geometrical space visually accessible from its vantage point. This is not what isovists were intended to represent. Isovists are assumed to carry information - information potentially accessible (through the visual sense) by, and relevant to, a hypothetical human explorer of that space. Therefore, the overwhelming majority of isovist implementations implicitly or explicitly carry the following key assumptions:

The Information-Content Assumption. Isovists can be understood as containers for visual information available from the vantage point of the human perceiver. The shape and size of an isovist is meaningful and interpretable *because* it is assumed to carry information. This can be information as basic as understanding the shape of the surrounding space. Different information can be relevant in the context of specific analyses, for instance: the potential attractiveness of the view (Shach-Pinsly, et al., 2011), co-visibility of settlements (Brughmans, et al., 2015), navigational choice available at a junction (Meilinger, et al., 2012), or emotional associations with the geometric shape of space (Wiener et al., 2007).

The Human-Standpoint Assumption. In the majority of applied architectural analyses, the vantage point of the isovist(s) is considered to be corresponding to a possible location of the eye of a human occupant, or to a location potentially visible by an eye of a human occupant. Thus, the properties and dimensions of a human body are relevant in isovist analyses.

It is important to recognise that the existence of such implicit assumptions is not a drawback of the isovist concept. They guide the analysis when the researcher faces an arbitrary choice (such as what resolution of Visibility Graph Analysis to pick; how to fix the height offset in a 2.5D landscape viewshed model; which surfaces should be modelled as penetrable). They also ensure the ecological validity of the isovist analysis, allowing researchers to interpret it with regard to the human experience.

It is the position of this paper that directly extrapolating the traditional 2D analysis into the third dimension (in the form equivalent to the `visible geometrical space surrounding the vantage point' - from now on referred to as a `volumetric 3D isovist'), violates the information-content assumption. In consequence, the volumetric 3D isovist computation does not fulfil the same function as its 2D predecessor was envisioned to.

We develop a novel approach of *embodied 3D isovists* that adopts richer notions of 3D visibility by distinguishing semantic, meaningful sub-regions of the traditional volumetric 3D isovist. We derive the semantic sub-regions by explicitly incorporating inherent, qualitatively salient properties of space, primarily orientation, as well as the semantics of the environment itself with respect to the affordances of human visuo-locomotion. We formalise these sub-regions as classes within the Building Information Modelling (BIM) paradigm, by extending the 'range space' *spatial artefact* class (Bhatt, et al., 2009; Bhatt, et al., 2012). We show how novel metrics that analyse changing relationships between these sub-regions capture key distinctions in the subjective visual impression of various environments. We have developed a prototype software tool for computing the embodied 3D isovist, that we use to demonstrate our metrics in exemplary scenarios[1].

We emphasise that our refined 3D visibility model is situated within Building Information Modelling (BIM), in the form of *spatial artefacts* (Bhatt, et al., 2009; Bhatt, et al., 2012) – surfaces in the built environment are not simply abstract geometric shapes, but are *objects* within a BIM: walls, slabs, ramps, doors, openings, furnishing, artefactual spaces, and so on. Thus, our visibility model is not only used to numerically quantify the geometric volumes and surface areas of visibility spaces, but can identify the classes (and unique identifiers) of objects that interact with our semantically meaningful visibility sub-spaces.

[1] We have implemented our prototype tool as a C++ plug-in to the BIM-based *InSpace3D* architectural design analysis system (Schultz & Bhatt, 2013). We implemented the 3D volumetric isovist generator using ray tracing. 3D visualisations were created using glc_player: http://www.glc-player.net/

2. LIMITATIONS OF VOLUMETRIC 3D ISOVISTS

The construction of our body and the workings of our visual system have consequences on how we move through the world, accumulate the visual information, and perceive the world. Our visual field is wider than higher (consider how we would see space if our eyes were aligned vertically on our forehead), and we move along the horizontal axes more than along the vertical ones. The result of this arrangement is that:

(a) **Horizontal visual information is easier to access than vertical information.** It is also more often relevant to our everyday operation. We *see more* horizontally than vertically and for the majority of the time we care more about what is located horizontally than vertically.

(b) **The right/left symmetry of our body and of our visual field is countered by the top/down *asymmetry* of our body and of the expected visual input.** Moving (or perceiving visual information) from left to right is relatively equivalent to moving (or perceiving) from right to left. Moving (or perceiving) from top to down is not equivalent to moving (or perceiving) from bottom up.

The above two features of human visual perception are not reflected in the volumetric 3D isovist analysis for two key reasons:

(a) Volumetric 3D isovists treat 1 horizontal unit of spatial information as equivalent to 1 vertical unit of spatial information.

(b) Volumetric 3D isovists do not consider any form of vertical asymmetry.

Both issues likely result from its direct extrapolation from 2D isovist implementations, as those are linked to the symmetric (horizontal) way of looking at the world and only afford quantification of the horizontal geometry of the visibility polygon. As a consequence, the volumetric 3D isovist is unable to model visual information in a manner relevant to the human three-dimensional experience of space. The way humans perceive the world horizontally is not equivalent to the way they perceive the world vertically. In practical terms, a person faced with a real-world task inside a building, be it dynamic (e.g. `find room 103'), or static (e.g. `express how much you like the entrance hall'), will not explore, visually sample, or remember horizontal information in a manner equivalent to the vertical information.

A three-dimensional isovist representation aiming to describe the `experience-in-space' (Benedikt, 1979, p. 63) must account for the embodied limitations of human spatial perception, and the resulting cognitive strategies of spontaneous information acquisition. The volumetric 3D isovist approach fails to satisfy this requirement.

3. EMBODIED 3D ISOVIST

We define the *embodied 3D isovist* that enables the analysis of three-dimensional space grounded in the way humans perceive and explore information present in the visible shape of that space. In this section we present a sample operationalisation of the concept. We then demonstrate how the embodied 3D isovist differentiates between features of architectural space unaccounted for within the `classic 2D' and the `volumetric 3D isovist' approaches.

Our operationalised definition is based on three steps.

Step (1) Generate the volumetric 3D isovist (any standard method from computational geometry will suffice).

Step (2) Classify surfaces on the boundary of the isovist that meet surfaces in the environment according to absolute directions (top, down, left, right, front, back). We define the orientation of each surface based on the magnitude of the vertical component of the surface normal, with respect to the environment's spatial frame of reference[2]. Vertical surfaces are symmetrical - a

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[2] Intuitively, the surface normal is an arrow pointing perpendicular, away from the surface, e.g. the top of a flat floor slab has a surface normal of (x,y,z) = (0,0,1), where z is the vertical component. The length of surface normals are 1 i.e. they are normalized vectors.

left-hand wall affords the occupant the same set of actions, and perceptual experiences, as a right-hand wall. However, horizontal surfaces are not - floors are associated with different affordances than ceilings both in terms of actions they allow and information they are correlated with. For this reason, we consider vertical surfaces to be qualitatively equivalent; horizontal surfaces are classified as downwards facing surfaces (usually ceilings) and upwards facing surfaces (usually floors). In our prototypical implementation we defined: *top* surfaces (e.g. ceilings) having normals with $z < -0.8$, *bottom* surfaces (e.g. floors) having normals with $z > 0.8$, and *vertical* surfaces having normals with $|z| < 0.1$.

Step (3) Calculate the volumes of three-dimensional figures defined by the isovists' vantage point and the three types of surfaces (all walls, all floors, and all ceilings). In a cubic space, these figures will have identical `pyramid' shapes. Their apex will always be defined by the vantage point. This is demonstrated in Figure 1.

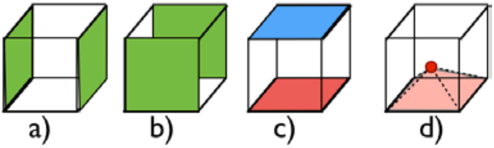

Figure 1 - Wall surfaces (a) and (b) are considered as equivalent, floors and ceilings (c) are considered to be distinct surfaces. Together with the vantage point, oriented surfaces are used to define the volume of a figure constituting each directional part of the 3D isovist (d).

3.1. APPLYING THE EMBODIED 3D ISOVIST

In the previous section we divided the isovist volume into semantically distinct regions based on the orientation of visible surfaces. We will now define relations *between* those regions.

Consider a cube with an isovist vantage point located in its centre. This defines 6 identical pyramids which share one apex. Each wall, floor, and ceiling surface defines the base of a single pyramid. The *height* of each pyramid is the distance from the base to the apex, in the direction of the normal of the base. The volume of a pyramid with *base* area and *height* is:

$$volume = \frac{1}{3} \cdot base \cdot height$$

We refer to pyramids with a floor or ceiling base as *vertical pyramids*, and we refer to pyramids with a wall base as *horizontal pyramids*. The relation of the average height of two vertical pyramids to the average height of all four horizontal pyramids equals 0.5 / 0.5 = 1 (further referred to as `vertical-to-horizontal', or *v-h ratio*). The relation of the top-surface pyramid volume to the bottom-surface pyramid volume is 0.5 / 0.5 = 1.0. This ratio will be referred to as `top-down ratio' (*t-d ratio*).

$$v\text{-}h\ ratio = \frac{\text{average height of vertical pyramids}}{\text{average height of horizontal pyramids}}$$

$$t\text{-}d\ ratio = \frac{\text{sum of top-pyramid volumes}}{\text{sum of bottom-pyramid volumes}}$$

A person 170 cm tall, standing in an average room of 2.5 m height, will have their `vantage point' located above the room's center yielding the *t-d ratio* lower than 1[3]. In the example case of a (very small) cube-shaped room with side length 2.5m, the *t-d ratio* is calculated as: top-volume / bottom-volume= ((1/3) x 2.5 x 2.5 x (2.5-1.7)) / ((1/3) x 2.5 x 2.5 x 1.7) = ~0.47.

In most common everyday situations, human height above the floor is fixed and rooms are rarely lower than 2.5 m. Therefore, *t-d ratio* much lower than 1 is unusual (although such a proportion can be associated with the observer standing on an indoor balcony near the ceiling - this situation will be reviewed later). Moving into spaces with high ceilings, on the contrary, is associated with a growing *t-d ratio*. Consider a larger cube of dimensions 50 x 50 x 50 metres with a vantage point fixed at 1.6 m above the centre of its floor. The *v-h ratio* in such a space also equals 25/25 = 1.0, reflecting the fact that the perceived shape of the environment, and the relation between the accessible vertical and horizontal information, is the same as in the smaller cube. The *t-d ratio*, however, is ((1/3) x 50 x 50 x (50-1.6)) / ((1/3) x 50 x 50 x 1.6) = (50 – 1.6) / 1.6 = 30.25, reflecting the perceived verticality of the larger space. Neither of these numbers change when the observer moves into the corner of the cube. Similarly to the measurands proposed by Benedikt for the 2D quantification, additional values can be obtained to reflect the position of the vantage point with respect to the boundaries of such a figure (e.g. based on the length and variance of distances to the isovist's boundaries). These are not explored in detail in the current article.

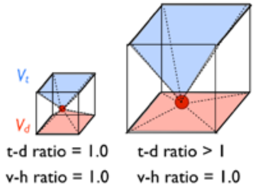

Figure 2 - Two cubes of different dimensions with a vantage point located either in the centre (left) or close to the floor (right). The 'horizontal pyramids' extending to wall surfaces are not visualised, but in both cases the average height of the two vertical pyramids divided by the average height of the horizontal pyramids yields the *v-h ratio* of 1.0.

Jointly, the *v-h ratio* and the *t-d ratio* can therefore describe the shape of perceived space, while differentiating between horizontal and vertical information, as well as between the information visible upwards and downwards (Figure 3). A space low and wide will have the *v-h ratio* much lower than 1, and the *t-d ratio* will depart from 1.0 as the observer's vertical position changes: the *t-d ratio* will grow if the observer has more information above, and will decrease when the observer is located closer to the ceiling. Conversely, a space which is narrow and high will result in the *v-h ratio* much greater than 1.

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[3] One might be tempted to consider the relationship between the volumes of vertical and horizontal pyramids. However, this does not usefully reflect the shape of an environment. For example, in a unit cube the ratio of the volume of vertical and horizontal pyramids is: 2 / 4 = 0.5. If we vertically *stretch* the cube into a tall rectangular cuboid then we might expect this ratio to increase reflecting greater vertical information, however *the proportion of horizontal pyramid volume to vertical pyramid volume stays the same*. This is because, while the height of the vertical pyramids increases, so does the surface area of the walls (i.e. the *base* of the horizontal pyramids).

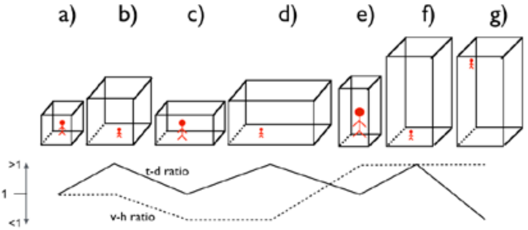

Figure 3 - A schematic (not to scale) representation of the relation between the *v-h ratio* and the *t-d ratio* in convex environments. Cases (a), (c), and (e) represent a vantage point located exactly in the middle of the space's height.

An example reflecting the need for the upwards and downwards distinction are patios with vista openings into multiple floors or balconies. Consider a simplified environment presented in Figure 4. The proportion of horizontal information available to the viewer is limited (i.e. quantified as the relative volume of the horizontal pyramids), therefore the *v-h ratio* reaches a value comparable with very tall but narrow spaces without such balconies. The environment presented in Figure 4 has the dimensions of 40 x 20 x 20, but its *v-h ratio* (derived for a `person standing' on the floor) equals ~2.6. A space without such balconies would need to have the dimensions of 40 x 20 x 78 in order to achieve the same *v-h ratio*.

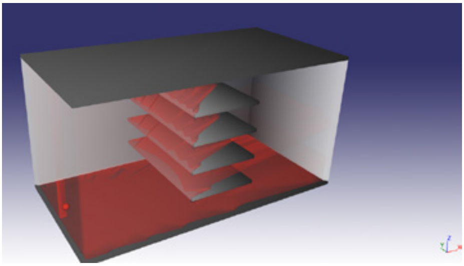

Figure 4 - A screenshot of the volumetric 3D isovist on a simplified environment of dimensions 40 x 20 x 20, with `balconies'. The vantage point is located 1.6 units above the floor, near the left hand-side wall. Note how the balconies occlude the visibility of the opposite wall. This results in decreased volumes of 'horizontal pyramids' (i.e. the portion of the 3D isovist that hits wall surfaces).

Distinguishing between very high and narrow, but convex spaces and those which are low but have many vertical occlusions is possible with `vertical jaggedness' - a measure analogous to the inverse of *circularity* defined for the 2D case (Benedikt, 1979). This can be defined as the cubic root of summed vertical isovist volume, divided by the square root of the summed surface area of all upwards and downwards facing surfaces (Figure 5).

$$vertical\ jaggedness = \frac{\sqrt[3]{\text{sum of vertical pyramid volumes}}}{\sqrt[2]{\text{sum of vertical pyramid bases}}}$$

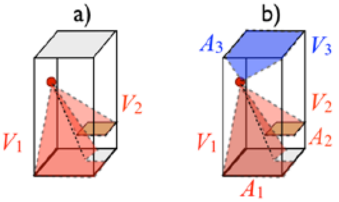

Figure 5 - (a) The total `downwards volume' is the sum of V1 and V2; (b) Vertical jaggedness jointly considers downwards and upwards volumes (V1+V2+V3), together with all upwards facing and downwards facing visible surface areas (A1+A2+A3).

Note how a change in vertical jaggedness affects the meaning of the *t-d ratio* (Figure 6). In a highly convex space, a low *t-d ratio* has a limited functional merit but clearly offers a different perceptual experience from a high *t-d ratio*. On the contrary, in a vertically `spiky' environment, its functional value is much more evident. Being able to easily see a large proportion of walkable surfaces has a different value in an environment that occludes them more often. It can also be speculated that seeing `a lot of air' above one's head has different aesthetic connotations in those spaces which are: (1) narrow, compared to those which are wide; (2) in those which are convex compared to those which are jagged; as well as (3) in those situations when we have a lot of information underneath us and those when we stand on the lowest bottom floor. Most importantly, interpretations of these measurands are not convertible: changes in *t-d ratio* values larger than 1 might have a different impact on human experience compared to changes in *t-d ratio* values lower than 1, even if the change is of the same numerical magnitude (Figures 6 and 7).

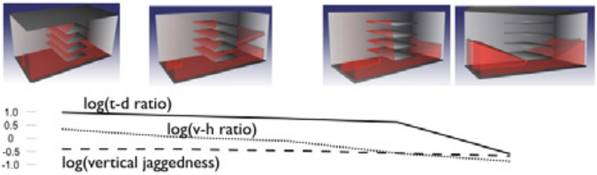

Figure 6 - The relation between three metrics depending on the vantage point's position in a mock up environment with balconies.

he implications of the distinction presented above will depend on the context of the analysis. Benedikt (1979) considers the Guggenheim Museum in order to demonstrate how a person moving along the ramp experiences almost no change in isovist (unless they step closer to the ramp's edge). While the volumetric amount of `range' visually accessible to the user indeed does not change throughout such a walk, there is a qualitative difference between being at the top and at the bottom of the ramp. This qualitative difference is relevant to the direct perceptual experience, as well as to the mental representation one can build based on the available visual information. As one moves downwards along the ramp, more and more `ceilings' become visible at the cost of `floors'. The navigator stops seeing surfaces from top-down, and is forced to perceive a larger part of the horizontal surface of the ramp from below. Firstly, this can affect the aesthetic experience of individual vistas. Secondly, it affects the amount of navigational choice one can realise from individual viewpoints. Humans can walk on surfaces that are facing up, but not on those facing down. Looking at the underside of ramps, from below, requires an additional cognitive step of inferring navigational actions potentially available on the unseen

top side of the ramp. This can be a non-trivial mental operation in some cases, but it is not equivalent to being completely unaware of the possible existence of these walkable surfaces.

Being able to view artworks hanging on the walls of the gallery can also be accounted for by the embodied 3D isovist analysis. In a gallery of a shape similar to the Guggenheim's, the fact that artworks are hung closer to the floor than to the corresponding ceiling of each wall means that the ratio of visible ceilings-to-floors is positively correlated with the occlusion of the artworks. As the visitor moves downwards along the ramp, they might be seeing the same total proportion of walls, but more of its crucial part (the one containing artworks) becomes occluded by the ramps that are visible from below (Figure 8).

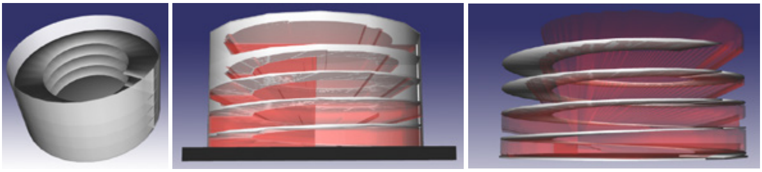

Figure 7 - Simplified 3D model of the Guggenheim museum with 3D isovists.

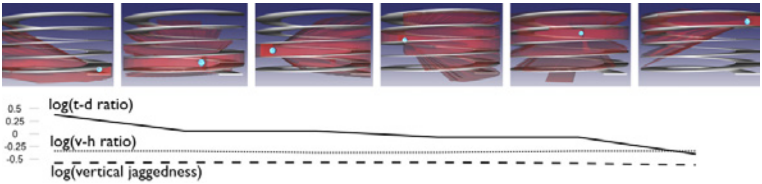

Figure 8 - As the vantage point moves upwards along the ramp, the visible wall surface area remains constant. So does the amount of vertical information (and therefore the ratio between the two). However, the type of the vertical information changes, reflected in the decreasing *t-d ratio*.

4. RELATED WORK ON 2D AND 3D ISOVISTS

4.1 IMPLEMENTATIONS IN 2D, 2.5D, AND 3D

The concept of isovist has been introduced by Tandy (1967)and popularised by Benedikt (1979). Despite considering isovists as three-dimensional on the conceptual level, early computational implementations were, by necessity, two-dimensional. They build on the familiar top-down approach of visualising building plans and operationalise the isovist as a polygon covering the portion of the environment visible from its single vantage point. In his seminal paper, Benedikt lists a number of metrics that can be used to describe such a shape, and suggests their relevance to the spatial experience of a building user.

Perhaps the most influential extension of the original notion has been proposed by Turner et al. (2001) with the development of Visibility Graph Analysis (VGA). In it, multiple isovists are generated from numerous vantage points at a fixed resolution, leading to the creation of a connectivity graph of individual isovists. This enables the study of entire buildings as a continuous space and accounts for visual relations between its subparts. Despite permitting to connect the graph across separate floors, Turner's original VGA is intrinsically two-dimensional, meaning that the method for calculating each individual isovist is based on `scanning' the space on a single horizontal plane around a vantage point in a top-down model.

As isovists were increasingly being applied in outdoor contexts (such as landscape planning), there was a growing need to account for three-dimensional visibility. Limited by the availability

of three-dimensional data, researchers utilised digital elevation models, in a `2.5-D' visibility analysis. This approach only accounts for a single z-value for each xy-coordinate, limiting its applicability in architecture, where a single wall can consist of many openings, or `holes'. Bishop (2003) and Llobera (2003) provide an extensive review of these developments.

The availability of new methods for sampling and storing three-dimensional data (e.g. Building Information Modelling and LiDAR) accelerated work on three-dimensional isovist implementations. Derix et al. (2008) presented a set of methods for calculating three-dimensional visibility inside architectural spaces. Based on the idea of the visibility graph, these methods can account for the average person's height, and quantify the changes in how open or constrained the space might seem to a potential navigator.

Lonergan and Hedley (2015) provide a broad review of recent approaches to modeling three-dimensional visibility, together with the contextual differences across these implementations. The authors expand the concept of an isovist's origin and target in order to account for the complexity of three-dimensional geometry in a manner relevant to common visibility analysis applications. For instance, a `point-to-volume' model can describe how a single human observer might visually access the interior of an apartment located in an opposite building. A `volume-to-volume' model would specify if any part of the target apartment is visible from any part of the origin apartment. It might be a design challenge to minimise such occurrences, without taking into account which exact parts of one's dwelling are visible from their neighbour's living space. In the similar urban context, Fisher-Gewirtzman (2016) presented a 3D visibility model which accounts for the semantic property of visible parts of the urban environment such as roads and dwellings.

Focusing on the architectural application, Varoudis and Psarra (2014) extended the traditional VGA approach to the third-dimension by accounting for accessibility affordances of floors. Their approach starts with defining `accessible' and `inaccessible' spaces in the layout, which are represented as a three-dimensional grid of isovist vantage points. A `mixed' visibility graph consisting of undirected and directed edges, is then generated. Classical `undirected' edges are created between nodes representing locations which can serve both as origin and as destination of a potential observer `looking out' towards the other node; `directed' edges represent connections between two spaces, of which only one can serve as a potential destination. This can reflect a situation when the observer looks at a void, high in the air above the floor's surface.

The focus on the relation between visibility and movement is traditional to Space Syntax, however the approach that describes human three-dimensional perception as the binary relation of visual and navigational accessibility is limiting. Firstly, it assumes that the human observer always knows whether a distant visible space is traversable or not. This leaves no possibility for modelling uncertainties and inferences involved in the exploration of space (information simply is, or is not available to the viewer). Second, it treats all spaces as equally accessible or inaccessible. This is not consistent with how humans perceive and act in it (e.g. considering all other factors equal, accessing higher ground is usually more effortful). Third, it gives equal weight to vertical and horizontal information, encouraging the assumption that seeing a tall, narrow corridor has the same perceptual effect as a wide, long room with a low ceiling.

Space Syntax as a discipline is believed to have detached the architectural analysis from the single viewpoint, putting the emphasis on the configurational properties of the whole space. But it is important to recognise that the primary units of that configurational analysis have originally been derived from the properties of human body and human cognition: convex spaces represent `areas potentially co-occupied by multiple people', axial lines are derived from the `longest lines of sight', and VGA relies on a `number of moves' required to see the whole space (see [Conroy Dalton, 2005] for a more comprehensive discussion of these implicit human-centred assumptions in Space Syntax). The problem hereby discussed seems to arise from the fact that these basic human-centred assumptions differ in the three-dimensional context and are invalid if simply extrapolated directly from the two-dimensional simplification. It is the goal of this paper to challenge those basic underling assumptions of the volumetric 3D isovist, and not to turn away from the configurational analysis back into the view from `the inside' of a

single observer. Further extensions of the presented work, and their inclusion in configurational methods such as VGA, is desired, but not implemented within this paper. The work reviewed above demonstrates how, in the third-dimension, richer notions of visibility are needed that take into account many more inherent properties of `space' such as orientation, as well as the semantics of the environment itself. To our knowledge, however, the existing implementation of 3D isovists treat space extending in each direction as equivalent, omitting the crucial role that vertical orientation plays in our perception of the environment.

4.2 ISOVISTS AND HUMAN COGNITION

In the two-dimensional context, research investigated the predictive role of isovist properties in relation to human visual perception and spatial cognition. Conroy Dalton (2001) and later Meilinger et al. (2012), linked characteristics of `partial isovists' to navigational behaviour of participants exploring an immersive virtual environment. Wiener et al. (2007) demonstrated how a small set of isovist measurands correlates with human navigational behaviour (such as finding the most/least visible place in the environment) and experiential ratings e.g. of beauty and spaciousness. In computer-based eye-tracking studies later applied to the outdoor context by Emo (2014), Wiener et al. (2012) demonstrated how the geometry of architectural space visible from the navigators' perspective can explain the preferred choice between two alternative routes. Both works demonstrated how extensively participants explored the horizontal axis of pictures presented to them (focusing on areas offering the longest `line of sight'), but superficially explored the vertical information further from the horizon. Both indoor and outdoor application of this paradigm demonstrated that the usefulness of vertical information (mostly containing floor and ceiling surfaces) is very limited in a spatial task, and therefore this axis is not extensively explored.

4.3 EMBODIED COGNITION

The concept of embodiment of cognition refers to the fact that human cognitive capacities and strategies depend on the organisation of the body, and therefore actions and processes afforded (but also limited) by it. This approach departs from Cartesian dualism of mind and body, as it assumes that cognitive representations cannot be studied separately from the physical properties of the world. A classic example of some implications are studies which linked positive evaluations of unknown symbols with the action of approaching (flexing arm), and negative evaluations with avoidance (arm extension) (Cacioppo et al., 1993). Robbins and Aydede (2009) provide an excellent primer on this and related concepts, known broadly as situated cognition. For the most comprehensive review of studies demonstrating how a broad range of other spatial cognitive processes is embodied and situated, see (Tversky, 2009). Part of the situated cognition approach is the view of the external environment as acting as `external memory' to our perception (Myin & O'Regan, 2009). It assumes that in real-life tasks people use the external world as a container for potentially relevant information. Knowing where to (visually) search for something is all we often need (see also (Tatler & Land, 2011)). As demonstrated by Wiener et al. (2012), the search for relevant information is not uniformly or randomly distributed in all space. Not all parts of space are equally expected to carry this required information.

5. DISCUSSION AND CONCLUSIONS

We have presented a model of 3D isovists that accounts for the embodied nature of the human perception of space. It also makes it possible to distinguish the situated context of the observer, such as the varying usefulness of top-down visibility in different types of environments. This is a semantic approach to modelling 3D visibility in the sense that we enrich the concept of visible space by defining meaningful sub-spaces (i.e. spatial regions that partition visibility space), based on embodied cognition.

Our model can be used as a basis for extending work known from the 2D implementation in a manner compatible with the available evidence from situated cognition. This is relevant to interpreting well-established isovist measurands in the three-dimensional context. Measurands

such as drift, revelation or jaggedness can have varying behavioral and cognitive correlates when differentiated across the vertical directions. Thus, their interpretation should not be extended directly from the empirical evidence using two-dimensional data and data collected in contexts with negligible need for acquiring vertical information.

A research goal introduced by this distinction is to establish what is the proportional importance of horizontal and vertical information in different contexts. This raises the challenge of representing such asymmetries in a holistic model of larger space. So far, aggregated visibility analyses such as VGA considered and aggregated isovists which all have the same `rules' of generating them and treated all information uniformly. If any asymmetries were considered, they would be identical across the whole modeled space.

In his review of Space Syntax' contribution to environmental psychology, Montello (2007) points to limitations of the isovist analysis. Applying a `one-size-fits-all' visibility representation falls short in accounting for known contextual and interpersonal differences in spatial cognition. In this paper we argue that accounting for direction is one of the required building blocks for a concept that Montello calls `weighted' or `probabilistic' isovists - a representation that not only conveys what is possible to see, but what is likely to be seen (by differing groups, in differing contexts). This requires reviewing the very basic assumptions of isovist analysis in order to align it with the established evidence on how human users explore, perceive, and cognise architectural space.

ACKNOWLEDGMENTS

Jakub Krukar's research at the Spatial Intelligence Lab was supported by the ERC StRG Grant Agreement No 637645.

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CITIES AS ACCESSIBLE DENSITIES AND DIVERSITIES:

Adding attraction variables to configurational analysis

LARS MARCUS
Chalmers University of Technology
lars.marcus@chalmers.se

META BERGHAUSER PONT
Chalmers University of Technology
meta.berghauserpont@chalmers.se

EVGENYIA BOBKOVA
Chalmers University of Technology
evgenyia.bobkova@chalmers.se

ABSTRACT

The central variables in any urban model are distance and attraction (Wilson 2000). Space syntax research has contributed to the development of new geometric descriptions and measures of distance that have proven successful when it comes to capturing pedestrian movement (Hillier & Iida 2005). However, the description and measurement of attractions has not been central to the field. An important exception is the development of Place Syntax analysis, which concerns new methodologies and software that opens for analysis not only of different kinds of accessibilities in the street network in itself, but also analysis of the accessibility within the network to different forms of attractions, for instance, residents or retail (Ståhle et al 2005). Importantly, these analyses are able to use the novel distance measures developed in space syntax.

Place Syntax analysis is a generic form of analysis, why we may choose to analyse the accessibility to particular socio-economic attractions, such as residents or retail, but we may also conceive of a model of 'pure' spatial form – a kind of architectural model of the city – where we substitute socio-economic attractions for attractions of spatial form. For instance, Place Syntax analysis has been applied in different kinds of density analysis, transforming density measures from area-based measures to location-based measures (Ståhle 2008). Such density analyses can concern density of socio-economic attractions such as residents or retail. But it can also concern analysis of density of built form, for instance transforming densities of floor space to accessibility to floor space (Ståhle 2008, Berghauser Pont & Marcus 2014).

In this paper, we extend such spatial attraction to not only include the variable of density but also diversity. Earlier empirical studies have shown strong indications that there is a correlation between the degree of land division into parcels (plots) and the diversity of socio-economic content, such as residents and retail. This can be measured as area-based measures, such as parcel density (Marcus 2000, 2001), but also as location-based measures, such as parcel accessibility (Marcus 2005). Importantly, in the latter case this can be analysed using place syntax analysis and space syntax measures of distance.

Finally, we present preliminary results from an empirical study of Stockholm, Sweden, where we test these measures both combined and individually, paving the way for more substantial empirical investigations.

KEYWORDS

Accessibility, density, diversity, attraction, configuration

1. INTRODUCTION: THE NEED FOR AN ARCHITECTURAL MODEL OF THE CITY

The last decade has produced convincing proof that the world today is facing environmental threats on an unprecedented scale (Brito & Stafford Smith 2012), and that these stretches beyond the today predominant issue of climate change (Rockström et al., 2009). In extension, current global urbanization processes, where two thirds of the world's population are expected to live in cities by the year 2050, put acute stress on urban and ecological systems to support social cohesion and human wellbeing. This brings unprecedented expectations on the future governance, planning and design of cities with knowledge demands that these practices not necessarily are prepared for; there typically is an *implementation deficit* in current research on sustainable urban development.

In response to these challenges we will in the following present progress towards what we call an architectural model of the city that may support practice in urban planning and design. The fundamental concern for any investigation of such an entity is the age-old discussion on the relation between humans and the environment, where the proposed model departs from regular conceptions of this relation through two fundamental shifts. First, the environment is here not understood as something given but rather as something created by humans. In cities, it is obvious how the environment that we take for granted as the framework for our everyday lives, not is something natural but constitute a human artefact. This has the important consequences that the environment is possible to shape according to different ideological principles that give preference to particular trajectories of socio-economic process.

Second, and closely related to this, the built environment is here not conceived of as an entity detached from humans and their activities, but as an inherent part of human progress in general; we simply cannot conceive of humans without an environment. In response to this the model presented here is rooted in a conception of urban space as an entity created not only in relation to the human body but also to human perception and cognition. More precisely, based on the theories developed by psychologist James Gibson about an ecological approach to visual perception (1979) and affordances (1977), the link between humans and the environment is here constituted by both physical and cognitive affordances emerging in the interface between human abilities and physical properties of the environment.

The outline of the paper is as follows. In the first section the proposed model will be described as fundamentally constituted in extension of the traditional gravity model, by measurable variables of distance and attractions (Wilson 2000), where in this case distance measures will be drawn from the extensive field of space syntax research and attraction measures from space syntax derived research using place syntax analysis (Ståhle et al. 2005). In the second section, such distance measures will be discussed in relation to the theory of affordances (Gibson 1986). In the following section, attractions will be defined as variables of spatial form in accordance with the overarching aim of an architectural model of the city, rather than variables of human presence or activity. This will take the shape of measures of spatial form that condition both density and diversity of human activity in cities. Importantly these measures will draw from accessibility research (Hanson 1959), but more precisely as interpreted in space syntax research (Hillier & Hanson 1984), in that they will be location based measures rather than area based measures (Berghauser Pont & Marcus 2015). Thereafter, these variables will be tested and evaluated against known socio-economic data on a set of urban areas in Stockholm. In the final section, conclusions from this evaluation will be drawn and based on these there will follow a discussion about next steps.

2. MODELLING CITIES: CHOOSING GEOMETRIC REPRESENTATION

The central variables in any urban model are distance and attraction (Wilson 2000). Space syntax research has contributed to the development of new geometric descriptions and measures of distance that have proven most successful, not least when it comes to capturing pedestrian movement (Hillier & Iida 2005). However, the description and measurement of attractions has not been central to the field. An important exception is the development of Place Syntax analysis (Ståhle et al. 2005), which concerns new methodologies and software that opens for analysis not only of different kinds of accessibilities in the street network in itself, but also analysis of the accessibility through the street network to different forms of attractions, for instance, residents or retail (Ståhle et al 2008). Importantly, these softwares include the novel distance measures developed in space syntax.

Hence, by an urban model we here mean a model of urban space based on physical and cognitive affordances for humans (Marcus 2015; Marcus et al. 2016). The benefit of such a model is that it allows us to better understand the interaction between spatial form and human activity, which is the primary driver in most urban systems. In extension, this opens up for the practices of urban planning and design to reshape the conditions for human activity and thereby redirect this in new trajectories, since spatial form is what is structured and shaped in the practices. Importantly, this opens for intervention also in more aggregated urban systems of human activity, such as social cohesion and local markets. In principle, it also opens for intervention in urban ecosystems (Marcus, et al. 2013).

As a generic point of departure for our endeavour to construct such a model, we have chosen the classic gravity model since it, however out-dated in many respects, extricates the essential variables for any model of cities. Hence, according to Alan Wilson the gravity model identifies three necessary components for an urban model, that is: means to measure *distance*, means to measure *attraction*, and a form for *representation* (Wilson 2000).

First, we address the issue of representation where one need to recognise the rapid expansion of possibilities that has taken place in recent decades in this regard, including digital techniques such as *cellular automata* and (Batty 2005). However, here we rather support our model on the rapidly developing field of network analysis (Newman 2010), that increasingly also is applied in urban modelling (Batty 2013). More specifically, we will build on the kind of architecture based description and analysis developed in space syntax research (Hillier 1996). We interpret the space syntax approach as architectural in the sense that it conceives of urban space as distinctly structured and shaped by architectural components of built form of various kinds, such as buildings, landscaping, and in some respects, traffic infrastructure. This approach differs in several essential senses from regular geographic models of cities. First, it explicitly aims to model the spatial form of cities as derived from the structure and shape of built form and nothing else. That is, it importantly does not include any socio-economic or behavioural data, a reason we choose to interpret it as a strictly architectural model. Second, there regularly are no longitudinal data in the model, that is, there is no included algorithm reflecting change over time. In this sense, it does not constitute a dynamic model, which may be another reason to call it an architectural model.

However, this does not necessarily imply that the models developed in space syntax should be conceived of as static representations or urban structure, rather we should pay attention to how the architectural origin of the models, emphasising built and spatial form and not least, putting great effort into the development of geometric representations thereof, in an original way bring back both behaviour and process to the models, at least to some degree.

First, network models, generally speaking, already imply process, since their very essence concern relations between entities and nothing else (Newman 2010). Relations here typically imply some kind of interaction between entities, usually expressed as flows (Batty 2013). Hence, while not being dynamic in a regular sense, where the structure of the model in itself change over time, we see that processes may still be written into the model by the fact that what it in the end represents is relations.

Second, what in the typical case is represented as entities in space syntax models, that is, the nodes or vertices between which we may describe relations by way of links or edges, is something quite peculiar, and differ from simple locations for origins and destinations, as one may find in regular urban models. In the for space syntax emblematic *axial map*, and its many derivations (Stavroulaki et al. 2017), urban space is defined by built form, in the manner discussed above, and broken up into spatial units defined by human visibility and accessibility, represented as straight lines (axial lines). Hence, in analysis, urban areas are represented as the least amount of axial lines covering all accessible space defined by built form.

It is important to emphasise how this form of representation based in the human affordances of accessibility and visibility, is of great principal interest since it signifies a fundamental shift in how space normally is represented in urban modelling. More particularly, it concerns a representation based in the conditions under which humans perceive, cognise and act in the environment, the reason we call it a representation of space defined by human affordances. This means that what is represented by the network model in this case neither is spatial form or human activity but the physical and cognitive affordances that appear in the meeting between the physical properties of the urban environment and the abilities given by the human constitution (Marcus 2015). Moreover, in an urban modelling context it has the rather peculiar consequence that 'streets' become nodes in the network and 'street junctions' links, where this in most urban modelling is represented the other way around, why it represents a kind of Copernican shift in urban modelling (Marcus et al. 2013).

These representations of urban space, furthermore, find strong support in certain strands of psychology, especially in the particular direction of environmental psychology taken by James Gibson, which he calls an *ecological* approach to visual perception (Gibson 1979). Gibson supports the idea that humans perceive the environment as a spatial continuum defined by physical form, whether natural or man-made, but that also is limited by the human faculty of perception. Moreover, he makes the argument that humans naturally move in the environment, which includes the movement of our eyes, the movement of our head and the movement of our body, why human cognition and action not only is informed by what is perceived in the present, but rather that places that earlier have been experienced and moved through, and our memories thereof, are an active part in determining human cognition and action. In a sense, therefore, Gibson summarises, we are always everywhere.

3. MODELLING DISTANCE: UNIVERSAL DISTANCE OR CENTRALITY

Such a conception of humans and their relation to the environment corresponds well with the notion of centrality, where each location not is defined by its limited relation to one particular other location, but rather to all other locations in the system. This brings us to the discussion about measuring distance in a network model defined in this fashion. In space syntax, distance is measured in a rather original manner. Hillier maintains, in accordance with the idea of human affordances, that we interact with space in cities both through our bodies and through our minds and argues that: "in bodily terms the city exist for us as a system of *metric distances*" (Hillier 2009:4), while our minds interact with the city through seeing, that is: "as a system of *visual distances*" (Hillier 2009:4). The argument for the axial line as a metric of distance can then be made: If we make a straight line crooked "we do not add significantly to the energy effort required to move along it, but we do add greatly to the informational effort required" (Hillier 2003).

Hillier next argues that: "we also need to reflect on the fact that cities are also collective artefacts which bring together and relate very large collections of people. The critical spatial properties of cities are not then just the relation of one part to another, but of *all parts to all others*" (Hillier 2009:4). "We need a concept of distance which reflects this" (Hillier 2009:4), Hillier concludes and proposes the notion of *universal distance as opposed* to *specific distance*, where the latter concerns our regular idea about distance, that is, as distance between an origin A and a destination B, while the first concerns the distance from all possible origins to all possible destinations in a spatial system. This distance measure is in spatial analysis more generally known as *centrality*.

Taken together this means that distance is measured as the mean distance from each node to each other node in the system, where these nodes are geometrically represented as lines, which here thereby becomes the distance unit. In regular network analysis, there are two primary measures of centrality; on the one hand *closeness centrality*, which measures the mean distance from each node to each other node in the system and, on the other hand, *betweenness centrality*, which measures how often a particular node is part of routes between all nodes in the system.

This conception of distance as cognitively defined that we find explicitly developed in space syntax and discussed in more principal terms in spatial cognition, furthermore proves most powerful when tested empirically. Extensive tests conducted in space syntax research demonstrate how distance measured topologically as amount of changes in direction, or geometrically as amount of angular deviation, both performs considerably better when it comes to predicting human movement behaviour than traditional metric measures of distance (Hillier & Iida 2005). Similarly, it has been shown over a broad range of thematic studies, including the perception of safety, the distribution of retail and the use of urban green spaces, how human movement is an essential, perhaps *the* essential, 'intermediate system' in explaining the influence of spatial form on such urban phenomena.

4. MODELLING ATTRACTIONS: ACCESSIBLE DENSITY AND DIVERSITY

Next, we address the issue of attractions, where we first stress the need to define attractions as an aspect of spatial form rather than as particular functions or amenities located in space, that is, by variables that capture how spatial form structures 'people and things' in space, rather than variables that capture 'people and things' in space themselves. We identify two fundamental variables of spatial form originating in the practices of architecture and urban design, first, the *densification* of space through the addition of floor space, whereby more 'people and things' can be stacked in the same location; second, the *differentiation* of space through the addition of walls and other forms of boundaries, whereby more categorical differences in 'people and things' can be delimited (Cf. Bobkova et al. 2017). The relevance of these variables is supported by an extensive review of the last decades' publications on Smart Growth, where variations on the variables distance, density and diversity proved to consistently reoccur (Colding et al. forthcoming).

For these dimensions of spatial form, we have chosen not to add further geometric description to our model but rather incorporate these dimensions by adding values for both densification and differentiation as attributes to the already existent nodes represented by lines in the model. This has the advantage of providing the possibility to, apart from distance, also measure densification and differentiation as variables defined by human affordances. What in effect is measured in our model is the accessibility *through* space to variables of density and diversity from particular locations, rather than measures of these variables as located *in* space as a local attribute to that particular location (Cf. Koch 2007).

More particularly, our measure of *densification* concerns the concrete entity of built floor space, but not as conventionally measured, that is, as amount of floor space per area of land, but as amount of floor space accessible through 'the street network' within a certain radius, and where this distance is measured in accordance with space syntax measures of distance discussed in the previous section. This adds up to a measure of human accessibility to floor space within a certain radius from a particular location. Obviously, what we are after is not floor space as such but the ability, in principle, through such densification to increase the number of people and things that are accessible from a particular location. This accords with the aim of our model to capture the general spatial potential of locations, rather than the specific and more momentary situation of concrete people and things found at a location, since the latter varies far more rapidly than the former. What our model captures here is therefore the long-term capacity of space to condition the number of people and things accessible to a specific location but not the more specific articulation of these people and things, which vary over time. However, we argue this to be an essential and critical property that on a most profound level conditions urban processes, not least from a sustainability point of view.

In a similar manner, our measure of *differentiation* concerns the concrete entity of built walls and other boundaries that define discrete spaces. However, in an urban context this entity multiplies to a degree that soon becomes unintelligible – there simply are too many physically defined spaces in a city if we include its buildings – why we need to look for a more generic spatial definition. We have identified this to be what in different contexts is called the plot, lot or parcel, that is, the spatial unit defined by land division, equally present in agricultural as in urban landscapes (Cf. Marcus 2000, 2001, 2005; Bobkova et al. 2017). We argued that this is the spatial unit that harbours and allows for the most fundamental of urban uses of space, that is to build, where to build here is understood in a broad sense and concerns the need in any land use to manifest, support and express any use in some kind of built form.

Since this means that we move to a spatial unit that primarily is defined by *legal institutions* rather that *physical form* it is important to stress the principal dimension of our variable here. While the legally defined spatial unit of the parcel may prove suitable to the level of cities, the physically defined spatial unit of the individual room would most likely prove appropriate at the level of the building and, stressing the principal character of the variable, we could even apply our measure in calculating the differential capacity of a chest-of-drawers by measuring its number of drawers (Cf. Bobkova et al. 2017).

Technically, the variable of differentiation is measured similar to densification, that is, as the number of parcels accessible through 'the street network' within a certain radius, where distance, again, is measured as a combination of physical and cognitive distance according to the discussion above. The two measures of densification and differentiation are then combined to constitute a variable of attraction, designated as attributes of each node in our network model.

Together, we argue, this constitute, a robust model of the city that at bottom is quite sophisticated, in that it embodies several original shifts from regular urban modelling, while keeping within a set of quite simple but established representations and measures.

5. TESTING AND EVALUATION: MODELLING ATTRACTION IN STOCKHOLM

In this section, we will test these fundamental measures of densification and differentiation, measured as location based measures, by making use of a large central portion of Stockholm, Sweden, where both the socio-economic characteristics as well as land-use distributions are well known. We will start by evaluating the measures individually and proceed to also look at them combined.

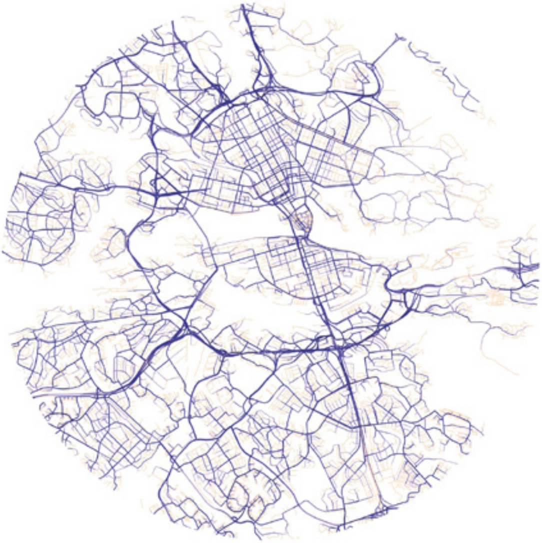

Figure 1 - Betwenness, radius 2 km.

5.1 BETWEENNESS CENTRALITY: GENERAL CHARACTERISTICS OF THE CASE

We may start by using the regular betweenness analysis as a means to characterize this portion of Stockholm. We see how the city is set within a landscape heavily fragmented by water into islands, with a central core defined by a rectilinear street network outside of which we find a far more hierarchical street structure with several loops and dead-ends. Also, these parts are in this sense fragmented into islands turning the over-all structure into a distinct archipelagic pattern, whether given by water or not. For the outer city, it is difficult to draw any distinct socio-economical conclusions from this comprehensive analysis, where we find similar patterns both for well-off single-family house areas and less well-off multi-family house areas. What stands out is the distinct difference between the inner city and the outer city, where there currently is a strong process of gentrification taking place due to increasing number of apartments being privately owned and therefore sold on the market, while earlier having been leased to set prices. As regular in cities framed by market prices, we see how centrality or accessibility to attractions, generally speaking, is a central driver of the socio-economic distribution of inhabitants. That this does not only is true in relation to geographic distance to the center, but also by the morphological structure of space as defined by built form is expressed by the discontinuity between the inner and outer city due to their distinct morphological difference, which also is reflected in housing prices (Bernow & Ståhle 2012). This is further reflected if looking at another variable sensitive to market prices, that is, retail distribution, which in the inner city follow the betweenness structure very strongly, while it in the outer city demonstrate a duality between, on the one hand, local centers planned in parallel with many of the multi-family house areas in the postwar era, and more spontaneous development along main traffic arteries serving these areas, where the first in many instances are facing decreasing market demand (Sayyar & Marcus 2013).

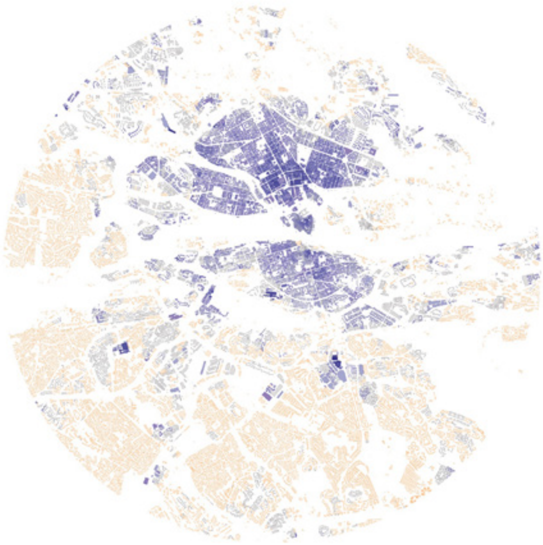

Figure 2 - Accessible Floor space, radius 500 m.

5.2 ACCESSIBLE FLOOR SPACE: FINE-TUNING SPATIAL CENTRALITY

Looking at accessible floor space, the earlier image is enhanced with an even more distinct leap between the inner and outer city, now created not only be a greater accessibility due to the grid-like street network, but further enhanced due to a generally far higher building density. Importantly, however, we also detect distinct chunks of very high accessibility to floor space in the outer city, which on closer examination turn out to be areas highly exploited for offices. Apart from these we also see a clear separation of the outer city into areas with low accessibility to floor space and areas with medium accessibility to floor space, reflecting, generally speaking, areas of single-family houses and areas of multi-family houses. Similar differentiation into areas can also be detected in the inner city, albeit not as accentuated.

Importantly, these varieties between areas in both the inner and outer city were not identified in the pure centrality analysis. Hence, we can see how the model proposed here, not only comprising measures of centrality within the street network, but adding to this the varying capacity for space in different locations to carry people and things, brings forth a richer image of the spatial form of the city and the socio-economic potentials it creates. One way of describing this is saying that by adding the distribution of floor space to the analysis, we achieve a more life-like image of the spatial centrality of the city, since it can be argued that centrality in this sense not only concerns accessibility within the street network, but accessibility to useable floor space.

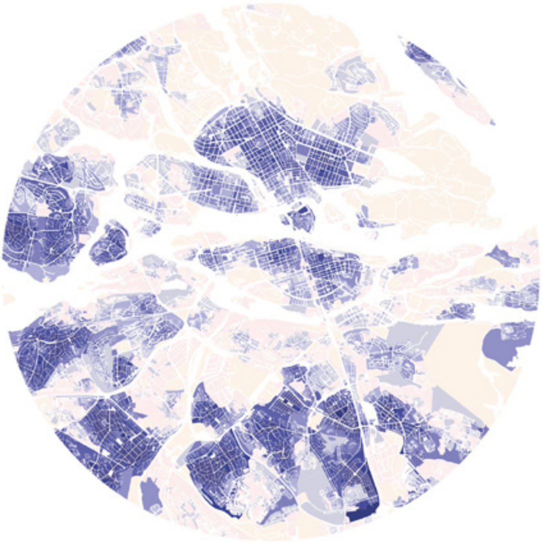

Figure 3 - Accessible Plots, radius 500 m.

5.3 ACCESSIBLE PLOTS: ADDING DIFFERENTIATION

While accessible floor space has been analysed and illustrated many times before in the attempt exactly to develop richer descriptions of urban density (e.g. Ståhle et al 2005; Berghauser Pont & Marcus 2015), the measure of accessible plots must be considered quite original with few precedents (Marcus 2001; 2010). In the image (Fig. 3), we also see a more unusual structure that immediately is not so easy to interpret. For one thing, we see how the outer city here to a substantial measure have higher numbers than the inner city. What we see are areas of rather small single-family houses set in rather grid-like street structure, thereby over-performing even the inner city, which in general also has very high numbers in this analysis. Interestingly, this analysis distinctly distinguishes the multi-family house areas from the post war era in the outer city, typically built within a far larger property rights structure than both the single-family house areas and the far older inner city. What also stands out are the areas for industrial use, with their typically isolated locations, albeit often with an internal grid-structure, and large plots.

The hypothesis that this structure somehow would reflect socio-economic diversity or diversity in land use, does not immediately seem validated by this analysis. Rather we would interpret areas with small single family houses as socio-economically quite homogenous (middle-class) and mono-functional (residential uses). However, if we ponder this question and take into account the strong influence on land-use regulations and building typology, we may detect rather strong indications that there is a quite powerful process of differentiation at work in these areas. Compared to the areas with multi-family housing, distinguished by their much larger plots, we may look at the far greater diversification in how both buildings and gardens/green areas are treated in the two areas, where this is far greater in the first areas despite the fact that far fewer people live there. We may interpret this as an indication that what may vary

within the rather strict land-use regulations found in both these areas, such as maintenance of buildings and gardens, truly seems conditions by the degree land is divided into plots. While the differentiating capacity of urban plot structure then seems easy to overrun by other forms of regulations, we do see a strong indication that this fundamentally morphological variable plays a part.

Hence, we do see a rather exciting image here, disclosing something that neither the pure accessibility to the street network or the accessibility to floor space displayed, and that actually seems to have something to do, not with amount and numbers, as the accessibility to floor space did, but with differentiation and degree of diversity. We may therefore see how this variable adds to the others, contributing to a richer architectural model of the city, which now not only captures the centrality of the city as structured by the street network, or how this centrality is biased towards amount of accessible floor space, since these places have the potential to carry more people and things, that is, the potential to carry more attractions. Now the model also captures the potential degree to which these attractions may be diversified, thus constituting a rich architectural model of the city describing the continuous landscape of potential accessibility to number and diversity of people and things that it presents.

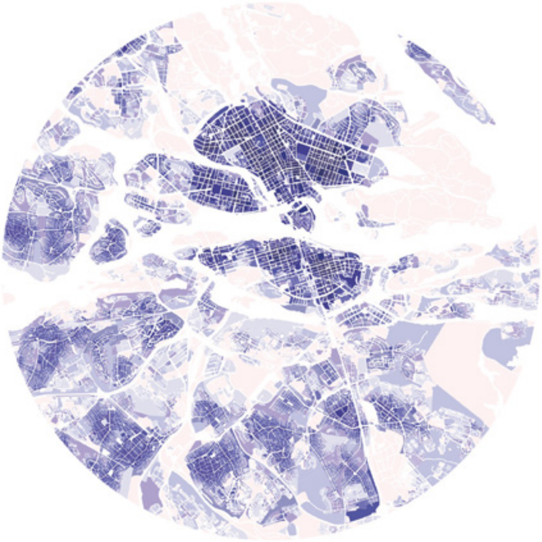

Figure 4 - Accessible Floor space and plots, radius 500 m.

5.4 ACCESSIBLE FLOOR SPACE AND PLOTS: AN ARCHITECTURAL MODEL OF THE CITY

Finally, we may combine the two measures of accessible floor space and accessible plots into one measure of spatial attraction, that is, capturing the spatial potential of locations to harbour both variations in number and differentiation of attractions, thus completing our proposal for an architectural model of the city. The procedure here is a simple multiplication of the numbers for both accessible floor space and accessible plots for each location. A tentative adjustment that need further study is to divide accessible floor space by 1000 due to the typically much larger numbers in this analysis than accessible plots. Naturally, this procedure needs further testing. However, albeit these being preliminary studies that need a lot more calibration, this measure capture a very life-like pattern throughout the city in terms of socio-economic characteristics and land-use distributions.

The inner city dominates with the highest numbers, but within this part of the city we also see a differentiation that quite closely follows the distinction of the inner city into areas of more varied content, what may be called the more busy areas, and the more residential parts. More distinctly, we see how we still find the highest numbers in the outer city in the single-family house areas, which may question how the model is calibrated in these particular analyses, but also makes the fact apparent, how these areas, while clearly being less dense than the multi-family house areas actually in many respects are more diverse. Interestingly, some of the more recent multi-family house areas with a far greater density than the post-war era areas and a greater centrality due to their location close to the inner city, stand out in the outer city with numbers coming close to the inner city.

6. CONCLUSION: TOWARDS AN ARCHITECTURAL MODEL OF THE CITY

While these results are preliminary and any conclusions drawn by necessity will be premature, we believe to have found most intriguing indications about how a typical space syntax model focusing on the universal distance or centrality of the street network, may be augmented into a richer model of the spatial form of cities by adding on the one hand, a variable of accessibility through the street network to floor space, and, on the other hand, accessibility to plots, also through the street network, which combined can be conceived of as capturing accessibility to potential attractions, thus constituting an architectural model of the city, displaying the capacity of the spatial form of the continuous landscape of cities to carry number and differentiation of people and things.

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THE THEORETICAL UNDERPINNINGS OF A THEORY OF SPATIAL CAPITAL

LARS MARCUS
Chalmers University of Technology
lars.marcus@chalmers.se

ABSTRACT

The world is witnesses unprecedented urbanization bringing extreme challenges to contemporary practices in urban planning and design. Global knowledge production has in response 'turned urban' leading to a tremendous out-put of new knowledge about cities world-wide from a broad range of fields. At the same time, it is increasingly recognised that what is lacking for a change of our cities into greater sustainability is not so much more knowledge about different urban systems as knowledge about how to change the trajectories of these systems – there typically is an implementation deficit in current research and knowledge on cities.

A typical character of contemporary research on cities, apart from the tremendous quantitative increase, is also its diversification into an extraordinary range of fields. Today Urban Geography, Urban Sociology, Urban Economics and Urban Ecology, which used to represent the periphery of their respective disciplines, are increasingly coming to constitute their core. Naturally this also builds barriers between disciplines, not so much due to disciplinary chauvinism as the simple fact that expertise in this academic range is near impossible to achieve. However, an alternative approach may be to look for what is common for all these fields rather than what is particular and when speaking of cities there is one such entity necessary for any discipline that want to call itself urban to address and that is space.

It has in space syntax research earlier been argued that space may constitute a "common language", whereby we may jointly understand social, economic and environmental systems in cities (Hillier 1999). This paper presents an extension of that ambition by presenting the outline of a theory of spatial form where it is argued how spatial form can be directly related to social, economic and ecological urban systems. To accomplish this, it also briefly refers to a model of urban spatial form that extends established space syntax models (Marcus et al. 2017), which primarily deals with distance variables, to also include variables of density and differentiation. The paper ends by arguing that due to the fact that spatial form to a large degree conditions the performance of more or less any urban system, it constitutes a form of capital that represents a tremendous value.

KEYWORDS

Sustainability, Urban systems, Urban models, Spatial capital

1. INTRODUCTION: A THEORY ABOUT SPATIAL CAPITAL

Current global urbanization processes, where two thirds of the world's population are expected to live in cities by the year 2050, put acute stress on urban and ecological systems to support environmental sustainability, social cohesion and human wellbeing. This brings unprecedented

knowledge demands on the governance, planning and design of cities of a kind these practices not necessarily are prepared for. In response to these challenges we here present a theoretical framework for a *theory about spatial capital* (Marcus 2010). Spatial capital is here understood as an extension of the fundamental value represented by *land*, but adds the argument that this value, is not only enhanced by investments in fixed capital, such as infrastructure, buildings and roads, but also by how the spatial form of land is structured and shaped through urban design, creating locations with specific socio-economic and ecological potentials. This value concerns both use values related to the everyday life of people as well as market values. The theory is underpinned by an analytical model of spatial urban form (Marcus et al. 2017), comprising the variables *distance, density* and *diversity*, whereby the entity of spatial capital may be measured and analysed.

The paper draws on a broad set of theories to demonstrate how spatial capital in this sense has a fundamental impact, not only on economic capital, but also on social and ecological capital. It is argued that the most fundamental asset in cities is people; however, the accessibility to people, the mobility of people and the distribution of the co-presences of people, are all phenomena structured and shaped by the spatial form of cities and it can be shown how such spatial relations have a decisive and long term effect on fundamental societal functions, such as social cohesion and economic markets, which in any society represents tremendous values in any respect of the word. Importantly, the same is argued for ecological capital, where the distribution of parks and green areas is essential for the functioning of urban ecosystems, which in turn are central for ecosystem services of many kinds that support health and well-being in cities of exceptional value. Together, we may see the contours of a broad theory of urban capital.

We will begin by interpreting current challenges in urban development, followed by a theoretical discussion about how spatial form in turn structures and supports the development of social, economic and ecological capital in cities. The paper ends with a brief discussion.

2. THE ONTOLOGY OF URBAN SPACE: THE NEED FOR AN ARCHITECTURAL MODEL OF THE CITY

While Jane Jacobs' succinct statement that: "cities are problems of organised complexity" (Jacobs 1961), went over the head of most scholars at the time (Batty 2005), it has now become a truism. However, while embraced in academic circles it does not to any substantial degree influence practice in urban planning and design. For someone daily occupied with the design of the physical form of buildings and cities, it is far from apparent how one is working with complex systems, the reason is that one is not. To unpack the confusing ontology of cities, there is reason to return to Jacobs' source to her statement, the tripartite categorisation of scientific problems by American Scientist Warren Weaver (1948). *Simple problems*, are problems constituted by few and independent variables, such as dealt with in Newton's laws of motion. Complex problems, on the other hand, either concerns problems with many and independent variables, called *disorganised complexity*, such as the movement of molecules in a gas, or problems with not necessarily many but interdependent variables, called *organised complexity.* This interdependence creates feedback and multiplier effects between the constituent parts of such systems, which make them highly unpredictable, as recognised in both social and ecological systems.

Hence, cities are complex systems, but they are so by integrating many systems of which some are simple. This is important, since discussions on complex systems typically emphasise their unpredictable behaviour, which hides the critical role of simple systems in complexity. As a matter of fact, such simple systems often rule over the complex. This happens, first, since complex systems, as we have seen, are decomposable, why we can make a distinction between interactions *among* subsystems and interactions *within* subsystems, where the linkages within a subsystem generally are stronger than the linkages between subsystems (Simon 1962). Second, since sub-systems constituted by physical matter, which typically are simple, are held together by far stronger forces than many complex systems, such as living systems (Schrödinger 1947). Third, since slow variables in complex systems have a tendency to dominate over fast variables and force them to adapt to their rhythm (Weidlich 1991).

This makes it reasonable to return to the ontological distinction of cities into systems of spatial form, the built structure of cities, and systems of temporal process, social and ecological processes in cities (Harvey 1969), where the first is a simple system and the latter a complex system. This opens our eyes to the critical role of systems of spatial form and the reason to humanity's tremendous investment in such systems; it has been a way to hold together, and in extension structure and shape, the typically weaker bonds found in social and ecological systems, that is, using physical structure to sustain particular social and ecological processes.

Hence, urban space is the central object of intervention in urban planning and design, that is, it is the 'material' whereby professional practice in these disciplines influence and direct urban systems of different kinds, whether social, economic or ecological, into politically sanctioned trajectories. More specifically, urban space is structured and shaped in these practices into spatial systems by way of different media, such as built form, institutions and discourse. We will here focus on how urban space is structured and shaped by the medium of built form in the practice of urban design, leaving the media of institutions and discourse, more characteristic for planning and governance, to the side, keeping in mind, however, the many overlaps between media and practices in these fields.

The challenge then is to develop representation of spatial form that can be linked to social, economic and ecological processes in cities, thereby allowing them to be consciously directed by urban design. It is here often repeated how the language of space is geometry, but the crucial thing is how geometry is applied in descriptions of space. Today, spatial descriptions most often have their origin in *geography* and spring form rather abstract conceptions of space (Marcus et al. 2013). For instance, space can geometrically be represented as a continuous grid or as a set of census areas, where the question whether these are adequate descriptions for the question at hand not necessarily is raised. Moreover, such representations typically describe 'things distributed in space' rather than 'the things that distribute space' (cf. Koch 2007), where we by the latter mean the variable of built form, why they do not really support urban design. Hence, there is reason to go to other disciplines dealing with space, such as *architecture*, where representations of space typically have their origin in human perception, and specifically are concerned with 'things that distribute space'.

For this we need a model whereby we can describe spatial form as structured and shaped by built form. This has been a central concern for *space syntax* since its origin (Hillier & Hanson 1984), where the most original contribution is the development of representations related to both physical and cognitive human affordances (Marcus 2015). These have typically been applied in different network based analyses of *distance* (Hillier 1996), but there has also been approaches that expands such descriptions to other dimensions of spatial form (e.g. Berghauser Pont & Marcus 2015). In the model underpinning the theory of spatial capital, these have especially concerned *density and diversity, measured as attraction*s for each node in the network (Marcus et al. 2017). Density is here measured as amount of built square meters, which repeatedly has been shown to correlate with population density (e.g. Ståhle et al. 2005), and diversity as degree of land division into parcels, which has been indicated to correlate with diversity in population (Marcus 2001). Together this presents an opportunity to describe the potential created by spatial form for the size and differentiation of co-presence for each location in the urban landscape (Marcus & Legeby 2011), something we can refer to as a spatial capital (Marcus 2010).

3. TYING SPATIAL CAPITAL TO SOCIAL CAPITAL: DURKHEIMINAN MICRO-SOCIOLOGY

However, for a theory about spatial capital we do not only need a technique whereby we can analyse and measure the spatial conditions for the distribution and co-presence of people in cities, but also a convincing theory about why the co-presence of people has a central impact on social relations and society in general. Of particular importance here are the theories of Emile Durkheim on *rituals* and their role as generators of emotional effervescence that tie together social entities, whether people and people, or people and things (Durkheim 1912). Durkheim

means that what fundamentally is celebrated in the rite, is the community it creates; the coming together of people in proximity creates an emotional fervour tying people together and in the end, it is that social bond that is both celebrated and sustained in the ritual; hence his conclusion that what is cherished in all religions is society. This idea was both specified and broadened by the American sociologist Erving Goffman into a general theory of *interaction rituals* (Goffman 1959, 1963, 1967). Goffman means that the kind of emotional effervescence typical for the rite is something we experience not only in religious settings but continually throughout everyday life, albeit on a lower key, why more or less any co-presence of people, however ephemeral or mundane, is understood to be part of the continuous recreation of society. Decisive here is the emotional interlocking and attunement that typically takes place between people in close proximity; sustained by glances, rhythmic speech and body movement.

The American sociologist Randall Collins has continued this micro-sociological tradition and expanded it into a broad sociological theory (Collins 2004). His point of departure is the fact that nothing adhering to human affairs really happens outside a *situation*, that is, Collins identifies human co-presence as the critical building block by which sociological theory can be built. Collins makes two essential additions to Goffman; first, he expands the central role of co-presence into a theory about how such situations of co-presence over time concatenates into a series, which he calls interaction *ritual chains*. Hence, he acknowledges the fact that we carry into every situation the experience of a series of former situations, which naturally conditions our experience of the new situation. Second, he unpacks the potential, inherent in Durkheim's theory on rituals, that these not necessarily only create solidarity, but potentially also conflict. A ritual seldom includes everyone in a given society, why it not only creates solidarity among the 'insiders', but potentially also varying degrees of conflict with its 'outsiders'.

Given the ability our model above gives us to demonstrate how spatial form is essential in generating the distribution of co-presences of varying size and differentiation in cities, we here see an important step towards tying spatial capital to social capital. The idea of social capital has its roots in the study of collective action, where concepts such as trust, cooperation and institutions are essential (E.g. Ostrom 1990). Its current popularity springs from the work by political scientist Robert Putnam (1993), who defines social capital as the "Collective value of all social networks and the inclinations that arise from these networks to do things for each other". There are many takes on the idea of social capital and there has also been extensive critique (e.g. Urry 2002). Here we rather aim to address how any take of such a theory has a spatial dimension. Putnam's version was supported by an empirical investigation of such variation in Italy, where he found that Northern Italy was far more successful than Southern Italy in implementing institutional change and that the main reason was its' more developed social capital. The result that the South was proven less able in this regard was surprising, considering its' tradition of strong family ties, why Putnam expanded on the character of the ties that build social capital. He found two types, *bonding*, which constitute social networks that hold homogenous groups together, and *bridging* that hold socially heterogeneous groups together. The type of particular importance for social capital are the latter, he argued, since such ties bring together a variety of social groups and competences and create a capacity for adaption and renewal. In contrast, bonds concerns groups of similar predilections that, generally speaking, does not contribute to trust and flexibility in the greater community.

In cities, we can see how these ideas contrasts with modern urban design, where the aim to create neighbourhood community often is the paramount ideal. The neighbourhood is a distinct local entity in an urban context and given the fact that there is a well-recorded tendency in cities of socio-economic clustering and neighbourhood effects, that is, a strong influence of local conditions on individuals (Wilson 1987), the focus on the neighbourhood must be interpreted as a policy for bonding rather than bridging. We may contrast the neighbourhood unit concept with the gridiron concept, such as Manhattan, which also exhibit distinct neighbourhoods, and make use of another observation by Jane Jacobs, namely that typical for Manhattan is a spatial overlap, where both local residents and visiting strangers tend to share the same urban space, that is, that residents and visitors tend to be co-present in the same street (Jacobs 1961). Hence, we could translate bonding into streets *without* overlap, primarily used by residents, and bridging into streets *with* overlap, used by both residents and visitors.

We then see why the latter kind of spaces may prove essential if we aim to build social capital; such spaces constitute spaces of higher 'information content' – the possibility that we get to see something that we did not expect. At the same time, however, we may also acknowledge a societal need of streets without overlap, where difference and even idiosyncrasy is allowed to develop, exactly to produce informational difference meaningful to exchange in the streets of overlap – without difference, there simply is no need for exchange. The point in the current context, is that we then see how spatial form works as a 'material substratum', in Durkheim's terms, conditioning the development of social capital, why it can be seen as a spatial capital, vital both in building social capital and sustaining it over time. Essential here is to understand how spatial form creates the conditions for a continuous landscape of differently sized and differentiated co-presences of people, something that has been demonstrated using variables in the model referred to above (Legeby 2013).

4. TYING SPATIAL CAPITAL TO ECONOMICAL CAPITAL: THE NEW ECONOMIC GEOGRAPHY

It is easy to see how the notion of cities as a landscape of co-presences of varying size and differentiation, in economic terms can be translated into a landscape of markets; what are economic markets but co-presences of people and things. This is reflected in the established explanation of cities in economics, which goes back to Alfred Marshall, who observed how certain industries clustered in particular locations (Marshall 1890). His explanation was that proximity offer firms externalities of which he identified three of particular importance. First, cities offer *knowledge spill-overs* in that proximity between firms in the same industry facilitates the learning from each other; second, cities offer *thick markets* where employers can find qualified labour and employees new work if laid off; third, cities offer both *backward and forward linkages*, where backward linkages concern producers' need to access input goods and forward linkages their need to access markets for their products.

While this argument has been embraced as foundational for urban economics, it has proven difficult to model and therefore remained an unverified assumption. The central contribution of the New Urban Geography (NEG) (Fujita et al. 1999) has been models that can test these assumptions. Modelling of space has a long history in economics and the scholars behind NEG identifies two strands. First, *urban economics* originating in the work of von Thünen (von Thünen 1826), which primarily concerns land use distributions in individual mono-centric cities, where they remark that models of this kind explain the land use distributions around existing cities but not the location of the city in itself. Second, *regional science* (Isard 1956), that spring from Christaller's analysis of the size and location of a set of cities within an area (Christaller 1933), which concerns the interaction between centres in regions and cities, that is, explaining also the location of cities in themselves. NEG continues the latter in the aim to model this tug-of-war between centripetal and centrifugal forces that decides the spatial distribution of economic activity and is the central object of study in urban economics.

When it comes to centripetal forces, that is, the attraction of cities on economic activity, NEG has for methodological reasons, focused on the externality of forward and backward linkages. Importantly, such linkages only make sense if it implies increasing returns for the individual firm so that it can impact firms' choice of location. Increasing returns, however, implies imperfect competition, which is demanding to model. Centrifugal forces; forces that discourage concentration, such as transport costs, may be equally difficult to model. It is overcoming these obstacles that have brought NEG attention. Sticking here to simpler variants of their models, it can still illustrate their arguments.

We may assume an economy of two regions and one manufacturing sector and then vary transport costs. In a situation of high transport cost we find an equilibrium when manufacturers are equally distributed between the two regions, since at a certain level of transport costs, prices and commuting costs will make it profitable for manufacturers to move to the smaller region; a process that will continue until they are equally distributed between the two. With low transport costs, in contrast, an equilibrium is found when manufacturers are concentrated in one region,

creating a core-periphery pattern, since low transport costs opens for a larger market leading to both higher wages (due to backward linkages) and lower prices (due to forward linkages).

We see the importance of transport costs in these models, something that may vary for many reasons, energy costs, degree of congestion and infrastructural standard. However, underpinning any such cost is physical distance, which is what routinely is structured and shaped by way of spatial form in urban design. Hence, we may say that urban design creates landscapes of locations with different and characteristic transport costs. The implications are two. First, that a model of spatial form of the kind referred to above may add exceptional resolution to NEG models, not limiting them to the idea of cities as having one or a few centres, but being constituted by continuous landscapes of centralities. Second, that urban design shapes and reshapes the distribution of centripetal and centrifugal forces in cities, thereby changing the spatial conditions for economic activity both locally and in aggregated form for the whole city. Hence, we see how spatial form is a critical means of production – a necessary capital – its' value typically reflected in the rent of urban land. Again, it is essential to understand how spatial form creates the conditions of a continuous landscape of differently sized and differentiated co-presences of firms, something that has been strongly indicated, using variables in the model above (Sayyar & Marcus 2013).

5. TYING SPATIAL CAPITAL TO ECOLOGICAL CAPITAL: ECOSYSTEM SERVICES

We now turn to urban ecosystems, which in cities are deeply intertwined with both social and economic systems. We will therefore refer to this conflation as social-ecological systems (Berkes et al. 1998), reflecting an understanding rapidly developing in ecology of humans as *humans-in-nature* rather than *humans-and-nature*. From having been something that ecologist turned away from – in the aim to study nature in its true state – urban ecology has in recent decades grown rapidly (McDonnell 2011). This is not least due to a new understanding of ecosystems as open, process-driven and regulated by external forces, where such forces can have their origin both in human activities, such as agriculture and urbanisation, and natural phenomena, such a fires and storms. Hence, humans are here understood as an intrinsic part of nature and ecological process.

This is reflected in how urban green areas have moved to the forefront in recent urban design and now are discussed for reasons beyond the recreational uses traditionally assigned to them (e.g. Waldheim 2006). Rather such areas are emphasised as carriers of ecosystems important for urban life and human well-being. This leads to new challenges for practice: how can spatial form harbour not only social and economic systems, but also ecosystems. Important here is the notion *ecosystem services* (Daly 1997), which concerns the great number of services ecosystems perform to the benefit of humans, such as pollination, air cooling and water cleaning, calculated to represent immense values also in monetary terms (Costanza 1997).

We may illustrate the idea through the ecosystem service pollination (Marcus et al. 2014). To facilitate such services in an urban area, we need to create support for both essential agents for this service, that is, pollinators, such as bumble bees, and processes, such as their foraging, nesting and breeding. Essential for this is to create a set of biotopes suitable for these processes as well as ensuring accessibility for pollinators between these biotopes. Hence, functioning ecosystems are in spatial terms a set of locations linked together in a configuration that allow movement between them. We then realise that the spatial demands of ecosystems not are very distinct from demands of socio-economic systems and that the inclusion of ecosystems in regular urban design is tenable. As a matter of fact, many regular urban design elements can be extended to also accommodate ecosystems (Barthel et al 2011).

For instance, it is apparent that ecological processes just as socio-economic are in need of accessibility between its different nodes of activity. Hence, the notion of the 'street', and similar spaces of flow, could be augmented to also facilitate ecological connections. In a similar vein, land in cities, just as agricultural landscapes, have through history been divided into discrete parcels for diverse activities and/or ownerships. Moreover, just as buildings are expressions of the need to enhance and intensify land-use through built form, they could be extended to support

ecological needs, for example: green roofs, green walls and integrated social-ecological water systems. Finally, just as with socio-economic systems, there is a need to set these elements into a systemic whole; a particular spatial configuration. In principle, this demonstrates the prospect of integrating ecosystems in urban design projects.

We may next contemplate how ecosystems and the services they produce, which create the very foundations for our existence, can be regarded as capital. The concept *natural capital* has generally come to concern natural resources, while we here aim for the systems that produce such resources. This has been called *green capital* (de Perthuis & Jouvet 2015), but has then been looked upon as something given, which limits the discussion to how to protect such systems; a static conception that can be questioned by pointing out how the history of humanity has seen continuous intervention in ecosystems; think only of agriculture. Our concern is rather to develop knowledge on how to support, improve or even create such systems, that is, invest in *ecological capital*.

However, it is obvious that ecosystems also are different from social and economic systems. Most importantly, while the agents in the latter systems are humans, constituting the primary flow in them, it can in the case of ecosystems be many different types of agents, such as birds and insects. This put new demands on urban design, albeit not as dramatic as one may think. The fundamental need is to adjust our model to a series of key species, in addition to humans, and acknowledge cities as a set of biotopes. Hence, we need to, first, relate all *distance measures* to these key species; second, relate the size and type of biotopes to these species; finally, adjust the *substrate* of the ground to these species to facilitate movement. Hence, also in regard of ecosystems it is essential to understand how spatial form creates the conditions for a landscape of differently sized and differentiated co-presences, this time of bio-topes, something that tentatively has been shown using variables from the model above (Berghauser Pont et al. 2017).

6. CITIES AS COMPLEX SYSTEMS: THE ROLE OF SIMPLE SYSTEMS IN COMPLEXITY

In the previous sections, we see a division of cities into two sets of systems, systems of spatial form and systems of temporal process, such as social, economic and ecological systems. We have also shown how the two are linked and influence each other, where the influence of spatial form on the co-presence of human and non-human agents has been vital. However, this is treating the dynamics of such systems in a limited sense. In our cases, people and other agents repeatedly generate social co-presences, local markets and urban ecosystems of similar size and differentiation and in the same locations. But what if this system is disturbed through a change of some kind, that is, acknowledging the true complexity of urban systems. To address this issue, we need to lift our discussion to another level and ask ourselves not only how spatial form support certain social, economic and ecological processes in cities, but how spatial form also sustain these processes over times of change. What we paradoxically are asking is what static structure can sustain dynamic change.

From our earlier discussion, we realise that what is surprising about cities and other complex systems, perhaps not so much are their often-emphasised irregularity and unpredictability – how could we expect cities to be anything else – but rather that they over long time periods remain so stable and predictable. This typical property of complex systems is called *resilience*, a concept introduced by Canadian Ecologist C.S. Holling (1973), in the effort to describe nonlinear dynamics in natural systems. Resilience has three interrelated characteristics, first, the amount of change a system can undergo and still retain the same controls on function and structure, second, the degree to which a system is capable of self-organization and, third, the ability to build and increase the capacity for learning and adaptation.

To support resilience in urban systems by spatial form, we need to identify, not so much the spatial demands for particular social, economic or ecological systems, as we have done above, but the spatial demands for resilience in these systems. Fortunately, such critical attributes of resilient systems have been identified (Berkes et al 1998; 2003). These attributes include *change, diversity, self-organization and learning* and have also been translated to spatial variables typical for our model above (Marcus & Colding 2015). Her follows a short review.

In resilience thinking *change*, is an inherent characteristic of all complex adaptive systems and therefore not seen as a threat but rather as necessary for renewal and adaption of a system. In urban systems, change can either have internal or external origins. External origins are related to the degree an urban system is connected to other cities and the following opportunity to receive new input, that is, it is related to the *variable* distance. Similarly, internal origins are due to the connectivity of different parts within the city, creating interactions and potentially innovation. *Diversity*, spreads risks by generating redundancy and creating buffers. In spatial terms, this is obviously connected to the variable *diversity*, that is, the division of land into multiple parcels, which can harbour, support and develop differences in human activity, and in extension in ecosystems. The capacity to respond to and shape change in productive ways is also a function of *self-organization*. In spatial terms this concerns the degree to which spaces that carry differences, such as different human activities, are connected to each other, so that these differences are able to reconfigure when facing change. Finally, there is the capacity in a system for *learning* in the sense of *memory*, that is, the ability of the system to retrieve lost information after disturbance. In spatial terms this concerns both distance and diversity, where more segregated spaces in cities can work as pockets of cultural memory that at a certain moment can inform, influence or inspire the city as a whole. Hence, creating spatial configurations in cities through urban design is a form of "writing" that, if correctly understood, creates memory of the social or ecological function the system is designed for.

Importantly, a typical ability of space is to carry many processes simultaneously; many trajectories parallel in time (Massey 2005). We can, therefore, create conditions for several of these attributes simultaneously, despite spatial form being such an unyielding material, simply by putting them in different locations. This is reflected in the idea in space syntax theory, that urban street grids, on a generic level, are constituted, on the one hand, by a *foreground network* that distributes high accessibility throughout the system and thereby facilitates socio-economic exchange and innovation and, on the other hand, a *background network* that throughout the system creates patches of secluded and undisturbed spaces that facilitates socio-cultural continuity and reproduction (Hillier & Vaughan 2007).

Due to its particular design, urban space can, thus, to varying degrees, simultaneously support parallel but different processes; on the one hand, allow for processes of change and, on the other hand, protect processes of continuity. In the end this needs to take the shape of particular configurations of spatial systems depending on the specificities of local contexts, however, our point here is to argue, that urban spatial form can be the object of design in the aim to not only support certain social, economic and ecological processes, such as the reproduction of social co-presences, local markets and urban ecosystems, but also in the aim to sustain and enhance the resilience of such processes.

7. CONCLUSIONS: HOW SPATIAL FORM UNDERPINS URBAN VALUES

We have here discussed how spatial form may support, structure and direct not only individual and fairly repetitive urban processes, such as social co-presence, local markets and urban ecosystems, but also how it may sustain such processes over times of upheaval and dramatic change; which we here argue is necessary if we want to transform our cities into greater sustainability. Importantly, we thereby do not say what processes are good, but rather that if we through political processes can agree on that, we here present tools whereby these processes not only can be spatially supported but also supported in a sustainable manner. Hence, it is also clear how spatial form in this sense represents a remarkable value – a value that enhance other values without self being spent – why it seems reasonable to speak of the spatial form of our cities as a *spatial capital*.

Spatial capital as we understand it here is closely related to one of the three fundamental sources of wealth in classical economic theory, that is, *land* (Brown et al. 2007) – the other two being *labour* and *capital*. While 'land' initially was understood as the prime generator of human wealth, its importance deteriorated under the neoclassical era in the first half of the 20th century; even to the point that when modern growth theory started to emerge in the immediate post-

war years, 'land' was not an integral part of the production function (England 2002). However, surfing on the tide of the growing environmental movement, 'land' has returned to the debate since the 1960:s, although, increasingly under the name 'natural capital' (Brown et al. 2007). In this context, it primarily refers to the fundamental resources provided by nature and necessary in almost any form of human production, a process we then may summarise as an interaction between natural *capital* and *human capital*, enhanced by what we today call *physical capital*, that is, different forms of machines or technological devices.

What we are looking for by the concept of spatial capital then, is an expanded understanding of 'land' as a source of wealth, which at the time of the classical economists primarily concerned the fertility of land. The point being that we may then not only envision investment in human and physical capital, that is, augment and improve these forms of capital both quantitatively and qualitatively through education and innovation respectively, but we may also envision investment in land. More precisely, our intention here is to address how the spatial form of both urban and natural landscapes, as structured and shaped by built form through urban planning and design influences the performativity of land, that is, the ability to enhance or invest in land by way of the design of its' spatial form.

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3D SPACE SYNTAX ANALYSIS

Case study: Casa da Música

FRANKLIM MORAIS
Escola Superior Artística do Porto, Oporto, Portugal
franklim@cyberoikos.com

JORGE VIEIRA VAZ
Escola Superior Artística do Porto, Oporto, Portugal
iorge@hotmail.com

DAVID LEITE VIANA
Department of Architecture, Nottingham Trent University, Nottingham, UK
david.leite.viana@gmail.com

ISABEL CRISTINA CARVALHO
Concinnitas Crl, Oporto, Portugal
isabel.cristina.carvalho04@gmail.com

CATARINA RUIVO
Faculdade de Arquitectura da Universidade de Lisboa, Lisbon, Portugal
catarinaruivopereira@gmail.com

CRISTINA PAIXÃO
Concinnitas Crl, Oporto, Portugal
cmartinspx@gmail.com

ANTÓN TEJADA
Universidad Politecnica de Madrid. Madrid, Spain
antontejada5@gmail.com

TIAGO GOMES
Concinnitas Crl, Oporto, Portugal
tiago60309@gmail.com

ABSTRACT

The paper will focus on research regarding DepthSpace3D: a 3D Space Syntax analysis software. This new digital tool increases the range of possibilities regarding 3D analysis, which seems to have advantages over current 2D analysis. The case study used to test those concepts was the iconic (and controversial) Casa da Música (by Rem Koolhaas, OMA) and its neighbourhood, one of the centralities of the City of Oporto. It will be argue that 3D can introduce something new to the Space Syntax analysis. The paper has three main goals: i) To analyse Casa da Música and its neighbourhood in its linguistic characteristics (syntax/connotational semantics) and in its functional relations (denotational semantics/pragmatics) to physical/social environment; ii) To compare 2D and 3D analysis (2D software is used to gather a set of data that is paralleled to

3D data); iii) To verify the obtained results within empirical data on human spatial behaviour, assembled from previous research conducted on the same site through automated video mapping. With this new approach, the paper will also reveals a new process to unveil how people use and appropriate its surroundings. Besides this framework, the outputs profits from some additional features of DepthSpace3D: transparency, multiple paths of visibility, attribution of properties to the Viewed Space.

KEYWORDS

3D SPACE SYNTAX, FORMAL METHODS IN ARCHITECTURE, NEW METHODS OF SPATIAL ANALYSIS, MAPPING, REM KOOLHAAS

1. INTRODUCTION

This paper intends to evidence simultaneously two different sets of assertions:

- one regarding the benefits of a 3D Space Syntax analysis digital tool, using for this purpose a case study - the *Casa da Música* in Oporto;
- another, advocating some architectural and urban considerations on the iconic (and controversial) case-study (by Rem Koolhaas, OMA) using, for this purpose, DepthSpace3D - a new digital tool for Space Syntax analysis.

When neither methodology nor its domain of application are well established, many problems of auto and cross false endorsement may arise.

To avoid such questions, validation was attempted by :

- supplying comparative studies using 2D Space Syntax proven methodologies;
- consulting other (non-formal) type of sources, in current architectural discourse and critique;
- gathering and processing empirical data using people tracking and mapping tools.

1.1 SO, WHY DEPTHSPACE3D?

Previous research developed on specific domains of Architectural and Urban Studies (A&US) using Space Syntax by the researchers involved in the DepthSpace3D project has confirmed the value of Space Syntax in the analysis of A&US. Nevertheless, some issues had been detected. For example, the global analysis of the city of Maputo (Viana, 2015) with intense use of Space Syntax 2D tools, could not deal with the problem of Maputo's altimetry. The intensive use of Space Syntax to study segregation and privacy in 13 collective housing enterprises in twentieth century Oporto (Ruivo, 2014) concluded that 3D analysis could improve the results. Although Space Syntax 2D could deal fairly well with the interior of each home and the middle-scale urban environment, it could not integrate the high-rise buildings as a whole in the context of the relation of the building and its near environment, treated as a unique domain of analysis.

At least, 3D tools may demonstrate to be of great usefulness in cases of rough topography of urban spaces; dynamic volumetric geometry: size, configuration, elevation and interpenetration; joint analysis of the interior of each building and its urban environment, in particular when there are high-rise buildings.

1.2 AND WHY CASA DA MÚSICA?

For the following reasons, *Casa da Músic*a is notably suited for 3D analysis:

- its interior space possesses a very intricate volumetry that is impossible to model two-dimensionally;
- a 2D polygon cannot suitably model its exterior surface, a 3D polyhedron;

- the ground of the *Casa da Música* square is moulded in curved surfaces, not prone to flat visibility;
- visibility between the inside of *Casa da Música* and its urban environment is established through a set of non orthogonal windows at diverse heights;
- one of the surrounding squares is filled by a garden with several plant species, at diverse heights.

The development of the research in *Casa da Música* led to the distinction of two different case studies:

- the global volume of *Casa da Música* and its urban environment, with little consideration of its interior; this study deals essentially with visibility analysis;
- the interior of *Casa da Música*, dealing with visibility issues, but also with the shapes and space configuration of the interior space.

2. DATA SETS AND METHODS

2.1. CASA DA MÚSICA AND ITS URBAN ENVIRONMENT

This case study has been modelled in 2D and in 3D. The 3D model has some conceptual and operative differences from the 2D that are worth to be elucidated.

a) delimiting the case study

The first necessary operation was to geographically delimit the case-study within the globality of the city's urban space. 3D visualization must be taken in account when performing this operation, in order to avoid the 'disappearance' of sections of the environment that can affect the results. Possibly, some issues cannot be predicted solely through a 2D plan.

The case study considered a geographical delimitation encompassing the two squares (Boavista roundabout and *Casa da Música* square) and the first dozens of meters of the confluent streets.

Two issues were reported, although they were not considered:

- the monument in the centre of the Boavista roundabout is visible from a much larger area, but it was not the kernel of the case study;
- the intended visibility of the sea from *Casa da Música* (that, at least, provoked the public controversy around the "hole" in the EDP building), would require a 6km analysis through a dense urban space.

b) three conceptual spaces: the viewing, the viewed and the obstacle spaces

The 3D conceptual model predicts three diverse conceptual spaces: the viewing space, the viewed space and the obstacle space.

The **obstacle** (to visibility) **space** is modelled by the surfaces of:

- the exterior of the volume of the *Casa da Música*; the interior is depicted by a minimum number of interior walls; some of the large windows are declared totally transparent (using a feature of DepthSpace3D);
- the facades of the buildings of the Boavista roundabout and the neighbour streets, since volume representation would not bring significant difference;
- the ground,whose only relevant topography is the curved shapes in the *Casa da Música* square;

- the trees in the garden inside the Boavista roundabout - three kinds of trees were considered, as an attempt to model the real diversity of the square: a majority of deciduous trees (with opacity varying from 15 to 80%, throughout the year), some evergreen trees (with permanent opacity of 75%) and palm trees. This led to two comparative studies, one for winter and one for summer conditions;
- the monument in the middle of the roundabout, a statue in a very high pedestal which is a distinctive historical monument of Oporto.

The active space for 2D analysis had to be divided in two conceptually different spaces in 3D. Contrarily to what happens in 2D analysis, the viewing space and the viewed space are not the same. For example, because it is unusual for people to fly, the **viewing space** - the space where the viewing subjects can move - is different from the totality of the studied volume. In this context, five different instances have been studied, resorting to DepthSpace3D's possibility of modelling many visibility paths:

- the cars, at 1m height;
- the pedestrians walking in the interior garden of Boavista roundabout, at 1,5m height;
- the pedestrians walking in the *Casa da Música* square, at 1,5m height;
- the windows of the buildings, at several heights;
- the windows of *Casa da Música*;
- as DepthSpace3D also enables composite paths, two other were considered relevant: the global pedestrian path (composed by pedestrians in the Boavista roundabout and pedestrians in the *Casa da Música* square) and the global path (union of all the paths).

Something else must be said about the viewing space:

- the paths are discretized in a small number of viewPoints - intense use of the DepthSpace3D software has proven that a very large sets of discrete points brings computational performance issues; fortunately, a smaller set of viewpoints lead to very similar results to those obtained with a larger set.
- each View Point has its 'volume of influence' (the volume of the part of the space represented by each viewpoint). They are also charged with a "weight", a calibration number that makes it possible to consider some other conditions. For example, the viewpoints of the car's path have a lower weight than those of pedestrians, considering:
    - the density of people in cars, against pedestrians density;
    - the lack of visibility from inside the car;
    - the minor attention paid by drivers to their surroundings.

The **viewed space** has two components:

- the urban surfaces; although conceptually different, they are physically identical to the obstacle space;
- the global volume, the surrounding 'air' that is modelled by a grid.

2.2. THE INTERIOR OF CASA DA MÚSICA

In the exterior, only visibility studies were considered. In the interior, besides visibility, this paper also attempts to study space semantics. While this doesn't bring any additional question in 2D analysis, where there is no conceptual identification of the problem (they are both achieved through the same tools), in 3D analysis, as we will see in c), this brings further issues.

a) delimiting the case study

The section of space considered in this case study is strictly the interior, delimited by the exterior walls. The relation between interior and exterior is studied in the precedent case.

b) three conceptual spaces: the viewing, the viewed and the obstacle spaces

When studying visibility, the three conceptual spaces remain the same. The obstacle (to visibility) **space** is modelled by the all the surfaces of the exterior and interior (walls, floors, columns and other elements) of the *Casa da Música*. The **viewing spac**e is the space where people can walk. The paths of the model are:

- the spectators path
- the staff path
- the visitors path

The **viewed space** has two components:

- the building surfaces, physically identical to the obstacle space;
- the global volume, the "air" that is modelled by a grid with 2m interspace.

c) the metamorphoses of the conceptual spaces

This is valid when considering visibility. What about space semantics? The surfaces are not obstacles to visibility, but the boundaries that establish the limits of and between volumetric (and two-dimensional) shapes. We could call it the **shaping surfaces**. This viewing space only concerns visibility studies. Space configuration studies don't use this data. The concept of viewed space also disappears.

The global **volume** is not viewed but is shaped by the shaping surfaces. There is also a change in the measured quantities. In visibility analysis, the base quantity is the visibility, the scalar function (that has values between 0 and 1) that relates all the points of the viewing space with the all the points of the viewed space. In space semantics, the relation is between any two points of the global volume and can take the value of 0 or 1, depending on the possibility to draw a straight line between them. Although the involved math is the same (visibility between two points is also given by a straight line) they can not be conceptually mixed up.

3. RESULTS

3.1. URBAN IMPACT

OMA's *Casa da Música* is located in a highly integrated area of Oporto, marking the beginning of an important axis which, extending 7km west, connects the city's centre to the seashore. The project was developed within Oporto's nomination for the European Union's programme European Capital of Europe, and both its location and function came following a strategy of cultural enhancement of Oporto's west, which had been reinforced by the development of a contemporary art museum and City's park between 1993 and 1999.

Figure 1 - *Porto's axial map*

The roundabout where it is located was built between 1866 and 1892, appearing in the context of an expansion of Oporto's public transportation, and would contribute for the establishment of a new centrality in the City.

From here, the development of a new urban axis, finished in 1915, allowed urban growth towards the ocean and contributed for the residencialization of an area that was previously un-urbanised and in the process of de-industrialization.

In the beginning of the 21th century this process was still not over, and, while the newly developed subway again helped establish this area as one of the better connected in the city, stressing it as an important centrality, the Boavista roundabout was still not completely defined, punctuated by derelict plots such as the one where *Casa da Músic*a was built.

While the target of heavy criticism at the time, the construction of the iconic building came integrated in an urban strategy in place from the 19th century. Located in an area which, however vital for the City's reconfiguration and for the establishment of a new centrality, was still undergoing a process of de-industrialisation and subsequent tertiarization, the *Casa da Música* was meant as a new pole of activity and urban attraction.

The part it played in both in an "internationalization" of the City (Tejada, 2016) and in the development of new, large scale equipments in the surrounding area has been discussed in the past years. To approach this question, the paper will focus on the building's impact on its urban surroundings, resorting to three-dimensional analysis software.

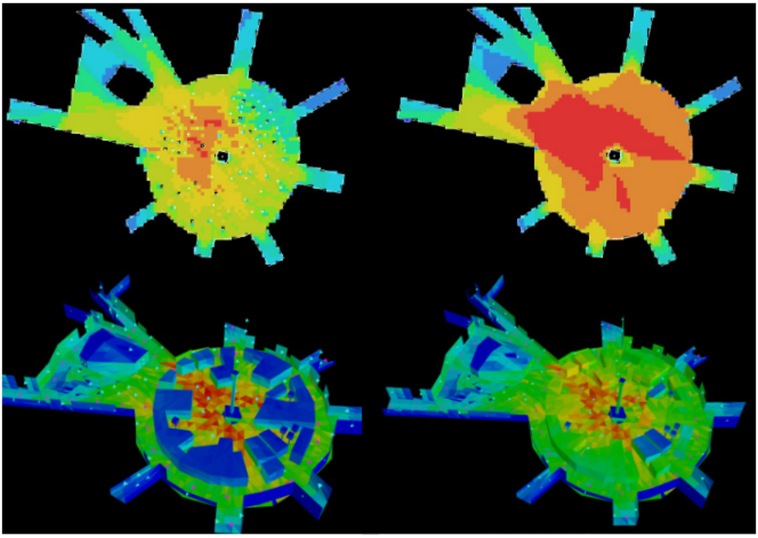

Figure 2 - Boavista roundabout and CdM's public space, limited by the surrounding buildings' facades. Visual connectivity values in 2D (with and without trees) and 3D analysis (different transparency values on treetops for Summer and Winter months).

While there are enough similarities between a two-dimensional and a three-dimensional visual connectivity analysis of the studied space to validate the obtained results, some differences should be noticed. In both cases: the most connected area is the part of the roundabout located in front of the *Casa da Música*, with values getting lower towards the surrounding buildings

and adjacent streets. However, it is interesting to verify how the trees in the square have an important impact on the visibility of the entire area, and how this translates to a three-dimensional analysis. On the one hand, it was possible to attribute different transparency values to treetops, representing their visual permeability during Summer and Winter months, and conduct two different analyses to understand how the connectivity values of the studied area shift throughout the year.

Then, it is also of note that even though a two-dimensional analysis is able to capture the visibility values for the periods when the trees are leafless, these cannot be read as corresponding to the associated facades. Due to the diminished visibility caused by the treetops, a distinct loss of perception of the buildings surrounding the roundabout could be verified through a three-dimensional analysis.

Taking into account the controversy generated around the construction of the new music hall, this is of particular relevance for the present study, as it allows for a more complete understanding of *Casa da Música's* presence and impact on its surroundings. If the iconic character of a building designed by a foreign star-architect, distant from local architectural tradition, seemed to easily attract wary comparisons to Bilbao and the Guggenheim effect (Ramalho, 2012), it seems to be difficult to argue that it causes any relevant disturbance in the existing city fabric. While the objectual nature of the project seems clear, the *Casa da Música* isn't granted a monumental status by its surroundings, presenting connectivity and visibility values not distant from those of the other buildings surrounding the roundabout. It is interesting here to draw a comparison between the requalification of the roundabout's garden and that of Oporto's City Hall avenue, both taking place during the period of intense urban regeneration which integrates the construction of the *Casa da Música*, and both authored or co-authored by architect Álvaro Siza. It is curious how the approach to existing vegetation and trees is strikingly different in both cases. In the same way its preservation seems to have great influence in the way a building such as *Casa da Música* is perceived - or not perceived - in the City, its complete removal from the avenue leading up to the city hall seems to reinforce the monumental and institutional nature of that space.

Volume attributes were used to explore this question further, both concerning *Casa da Música* and the monument for the heroes of the peninsular war located in the center of the roundabout. A noticeable issue, that highlights a special feature of DepthSpace3D, is worth to be reported. The historical monument in the centre of the roundabout appears in the Space Syntax analysis as a less visible object. But this is a misunderstanding of the conceptual framework of the performed analysis. The monument is not an explicit object in the model. The explicit objects are the surfaces of the monument. And each surface is seen by not more than half of the viewing space. In order to approach the model to reality, DepthSpace3D has a feature that consists in assigning attributes to sets of objects.

We can construct a new concept in the language - the monument - as a set of the primitive concepts: surfaces or points. And finally, we can see the visibility of the new object, an aggregation of all its primitives. This feature can easily extend from physical entities to abstract concepts.

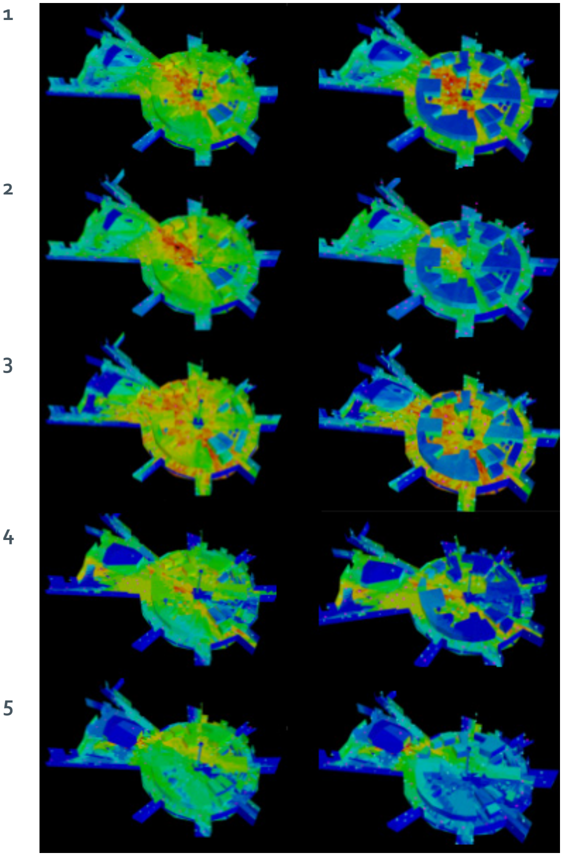

Figure 3 - Different paths showing different visibilities for Winter and Summer months (1.cars, 2.windows,3.pedestrians in roundabout, 4.pedestrians in square, 5.Casa da Música's windows).

Path analysis also seems to confirm that *Casa da Música's* impact is most felt from the public space resultant of OMA's intervention.From these it was possible to verify that the roundabout's garden is the most visually connected area and that, even though *Casa da Música's* public space is highly visible from its inside, the building is not. It is mostly seen from the surrounding buildings, whose different heights allow some of them to look both over the trees and other buildings, and by pedestrians on OMA's designed public space. Visual contact between *Casa da Música* and the exterior is also limited from the inside, with its large windows not allowing for a good perception of the exterior space. Even though, bi-dimensional analysis also allows for the study of different paths, the possibility of concatenating them in various groups, as well as attributing them different weights, contributed greatly for this analysis.

3.2. PUBLIC SPACE

Regarding public space analysis it was structured a methodological process combining the composition of a computational code (able to use tracking approaches with OpenCV) and data mapping to visualize space appropriation densities and intensities, defined by local and daily space users. Data visualization was developed through thermic maps and cumulative isocurves maps, that reveals main walking patterns concerning people's space dynamics and interaction within *Casa da Musica* surroundings.

The methodology set to study the public space was based on a three steps strategy involving video tracking, pattern recognition and dynamic mapping. After these phases, the information resulting from data collection and visual analysis methods was confronted with the outputs from DepthSpace3D, in order to verify its convergence with empirical analysis. Data extraction was possible due to the implementation of a pattern algorithm into Python, using OpenCV libraries, such as those used to computer vision (Computational Biometric) initially developed by Intel in 1999, that includes basic algorithms to people recognition. It is an open access library under BSD licence. The recognition process occurs due to an algorithm that removes video's background to get pattern's outline, through which sets a rectangular frame needed to track the movement in every video snapshot. The outcome of this process is an image full of dots concerning individual movements traced on the space (Figure 4).

Those dots extract from Python compose a file .TXT with rough personal space appropriation data regarding people's walking trends and spatial main tendencies structured within X and Y cartesian coordinates of the resulting grid from video processing. After this phase, the dots conversion process implies the use of a Rhinoceros plug-in called Grasshopper. It was then possible to proceed to data management collecting elements to set the main space appropriation patterns and produce information regarding people's dynamics and space interaction within *Casa da Musica* public space and its surroundings.

The thermal maps developed to *Casa da Musica's* space public analysis were structured to achieve space uses intensities visualization able to show the different kind of space densities attached to *Casa da Musica's* surrounding area. It was important to understand how that space was occupied within several space-time frames. These maps provided a range of colours between blue and red that translates the most used spaces (red) and those with less human fluxes and trajectories. One of the main constrains of these kind of maps is the difficult to extract a clear individual visualization, where one can identify single paths and space appropriations. To suppress this limitation, it was developed a set of isocurves maps resulting from graphical computation approaches. The main goal of the use of this kind of data visualization was to get individual space occupation patterns defined by proto-geometries, that expresses people's space dynamics and its convergence into collective spatial intensities, also through a wide colour range implying different space performances and group space sensitivities.

On the other hand, the cumulative isocurve maps were based on the accumulation of dots extracted from different mapping methods and its articulation with the same kind of algorithm used on step one of the process, when defining the isocurves maps ("metaball"). The algorithm makes the isocurves as an average result of the distances between every points. It was possible to get cumulative isocurve maps regarding *Casa da Música's* public space, where one can observe distinct space densities which reveals how *Casa da Musica's* surrounding area pulse and establish links to other parts of its neighborhoods and the City in terms of paths' continuity, visual connectivity, overall and sectoral visibility performance. To achieve it, it was necessary to complement *in situ* survey and empirical approaches/video tracking with formal methods (Viana, Franklim & Vaz, 2015) like the one provided by DepthSpace3D.

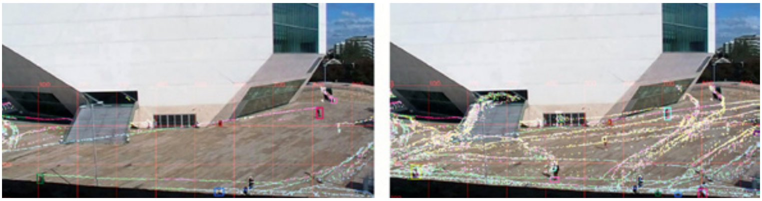

Figure 4 - Tracking space dynamics and individual paths using video and computational/digital methods to capture personal appropriation and fluxes within *Casa da Música's* public space.

When analysing *Casa da Musica's* surroundings it can be said that the spatial relation between local visibility and patterns paths have similar performance. For instance, Figure 5 shows (for Winter time) the main crossing area between *Casa da Musica's* square and Boavista roundabout. It reveals the interdependence within the transitional space promoted by *Casa da Musica* roundabout facade and the less presence of trees within the zone.

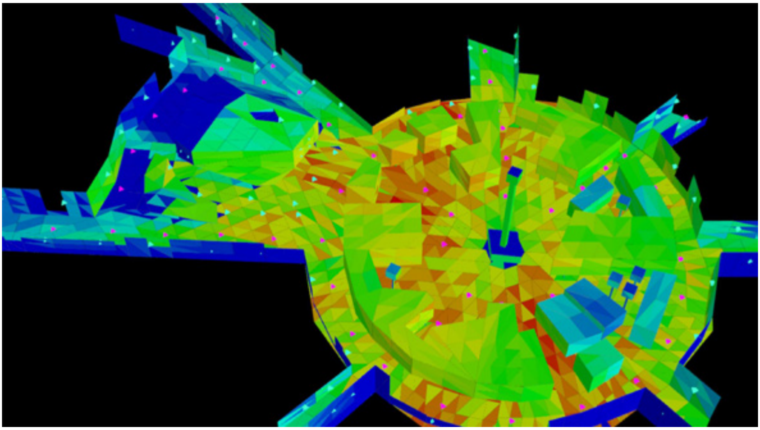

Figure 5 - DepthSpace3D visibility analysis of Winter time, with visibility points and viewed surfaces, where it is possible to verify where people tend to cross to *Casa da Música's* square.

If one attend Figure 6, it possible to check that the result provided by DepthSpace3D to Summer period also maintain the same area as one with best visibility performance. It is important to confront Figures 5 and 6 with people's space dynamics visualization to understand how individual and collective approach is made to *Casa da Música*.

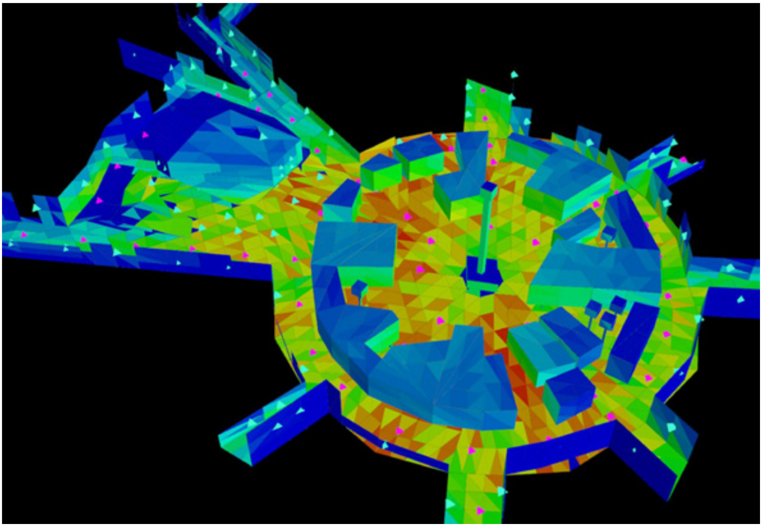

Figure 6 - DepthSpace3D visibility analysis for the Summer period, with visibility points and viewed surfaces, involving the spatial relation between Boavista roundabout and *Casa da Música's* surrounding public space.

Another important aspect, as already mentioned, is to know the type of "pulse" that characterizes *Casa da Música's* surrounding public space. Therefore, let's go back to the already interconnected referred notions of density and intensity. According to Figure 7, the major part of the maps with colorful areas occurs in the main accesses to *Casa da Música's* square The isocurve map reflects how influential those spaces are regarding entering into Casa da Música's surrounding public space. The main entrances to *Casa da Musica* also have an important role concerning this result (Figure 7).

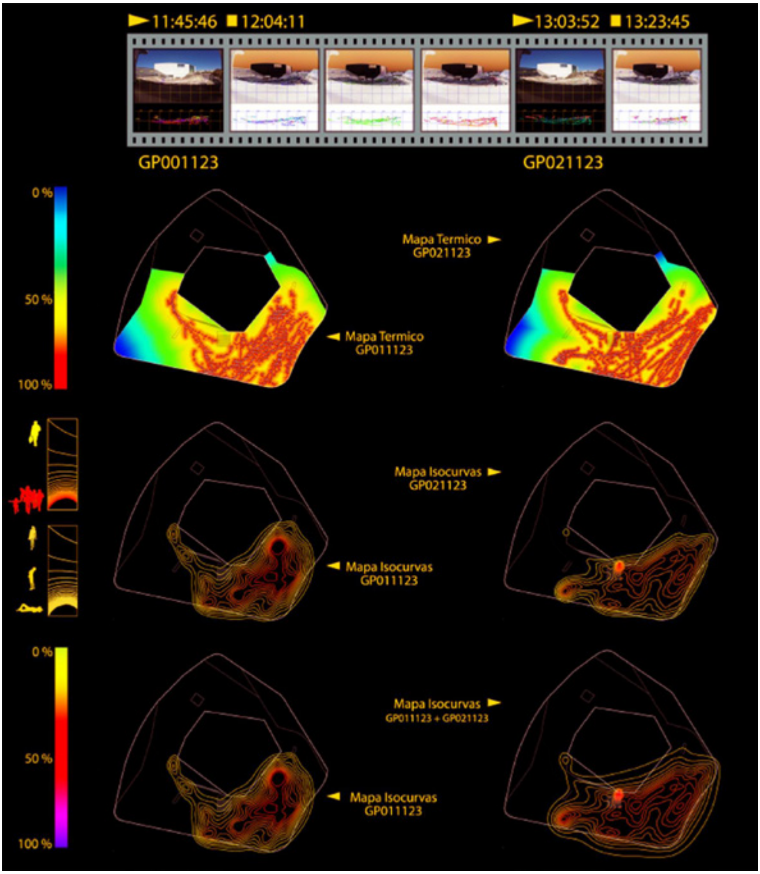

Figure 7 - Thermal and isocurve maps of *Casa da Música's* public space in a Winter day.

Regarding local intensities, Figure 8 shows that the main tendencies sets into intermediate areas that one can find between the principal entrance areas to *Casa da Música's* surrounding public space. From these sort of results it is possible to say that it is more relevant to people's local spatial uses and appropriation the sensitive dimension of the space rather than how it is perceived.

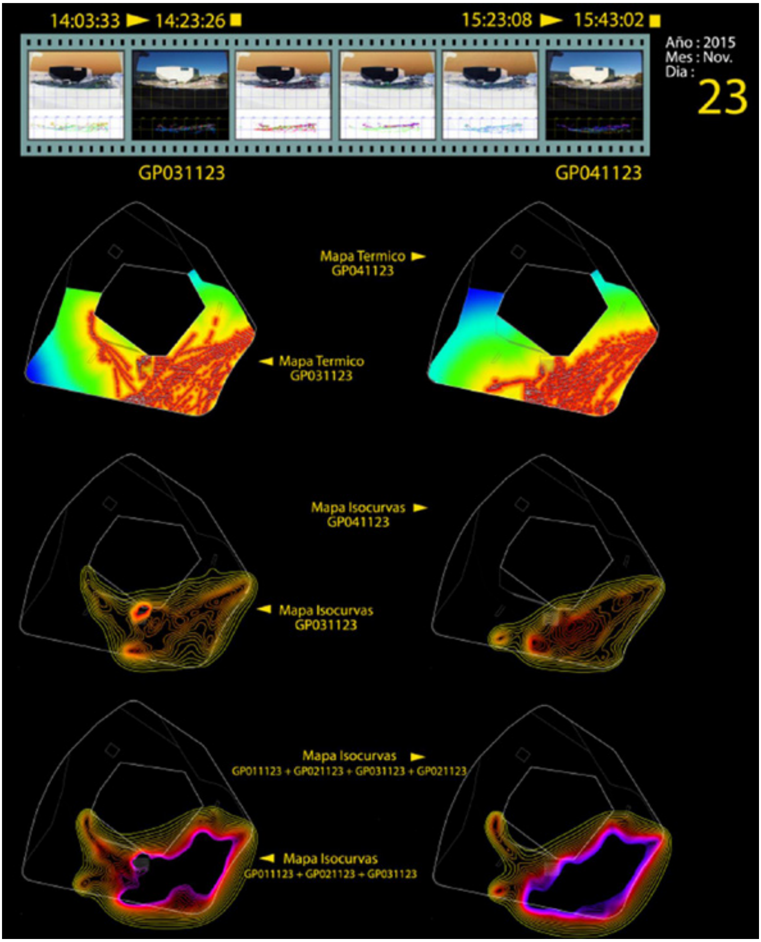

Figure 8 - Empirical tracking, data digital visualization and computational analysis of *Casa da Música's* and scripting to verify the convergence between intuitive approaches, qualitative and quantitative methods, space sensorial qualities and space body experience and perception.

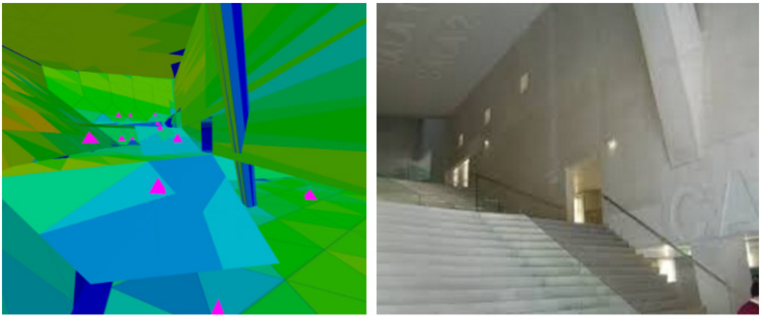

Figure 9 - Connectivity of Casa da Música's entrance hall and main staircase, with photograph for reference.

The complexity of OMA's building poses a challenge for the analysis of its interior spaces. Justified graphs are clearly useful for the systematization of the existing spatial relations, but traditional analysis through axial, convex and visibility maps proved both difficult to achieve technically, and risked being unreliable in translating the entirety of *Casa da Música's* spatial intricacy.

While it seems possible, if not practical, to study the social relations taking place inside the building through two-dimensional analysis, three-dimensional tools seem essential for getting a full grasp of the total complexity of its interior. As Figure 4 makes clear, using space syntax methodology for the analysis of the formal qualities of space and, for example, for an analysis of style, can greatly benefit from three-dimensional tools.

In this particular case, three-dimensional tools allowed for certain observations regarding Koolhaas' architecture, confirming design patterns and spatial qualities proposed in previous Space Syntax analysis of his work. (Dovey and Dickson, 2002; Zook and Bafna, 2012).

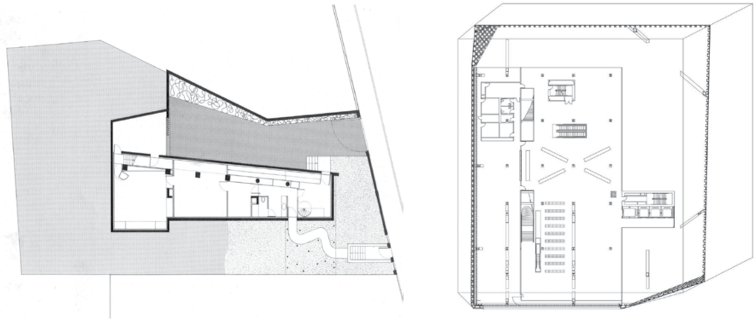

Figure 10 - Multiple vertical accesses in Villa Dell'Ava and Seattle's Public Library, by OMA

The multiplication of accesses seems to be a characteristic transversal to most of Rem Koolhaas work, from small scale to large complex buildings, resulting in the production of particularly shallow structures, with spaces highly connected between them and presenting low levels of control. In *Casa da Música*, there is a clear division in this aspect between private (such as

administration and services) and public spaces. While it doesn't follow the traditional structure of control where shallower spaces are allocated for visitors and deeper spaces for employees (Markus, 1993), private spaces follow a tree-like hierarchy of corridor-functional area, versus highly "ringy" public areas. In the latter, with the exception of the two concert halls and the restaurant on the terrace, there is little differentiation between programmatic areas and circulations.

Presenting no dead-ends (with the exception of restrooms), functions are integrated in a succession of ambiguous spaces and the resulting configuration seems to follow the same logic as described by Zook and Bafna (2012) for Seattle Central Public Library, were the building "enhances incidental movement into attraction spaces while limiting such ingress to the functions" (p.4). In fact, the two concert halls - easily the most important functions of the building, are accessed through contrived routes, while the ampler and better integrated spaces are often not associated to any official program.

The narrowness of the foyer gives it a very circulation character which, added to the greater integration of the large staircase shown in Figure 4, results in a shift of the foyer's original function to this space. The largest views, even though low control and poorly integrated spaces make it impossible to perceive the globality of the space from within the building, are usually possible from more segregated, almost "accidental" spaces.

4. CONCLUSIONS

The paper presents a new digital tool, DepthSpace3D, with its own theoretical background, methodological framework within formal methods (adding a 3D operational interface to visibility and configurational space analysis), and - through the application of this new digital tool to a real case study - it was demonstrated the potential of its semantic context and syntactic structure. Even as a brief induction to DepthSpace3D, the paper go forward to new possibilities to converge empirical space analysis based on video tracking and dynamic mapping with quantitative methodologies, narrowing the gap among each other. One of the main idea of the research is to set a wide platform of existing and new digital tools applied to Architecture and Urbanism able to work together within a combinatory and integrated design process, where analogical instruments can be complemented with computational languages and technological development in data collection, management and visualization, space information analysis, collaborative and shared design processes and participatory projects.

Space and data, formal methods and DepthSpace3D, community engagement and mapping, are being put together in a relational methodology in order to deepen the knowledge regarding people/space dynamics, flows and interaction, considering this equation on its multidimensional layers of transdisciplinary existence. The interoperability and proximity between different languages will put us closer to higher levels of hybridization, dialog and interoperability among several digital platforms and tools. DepthSpace3D looks forward to fulfill this mission. To do so, and regarding future steps, the ongoing research will set actions to put DepthSpace3D into the market with capacity to be not only an autonomous digital tool, but also to be part of existing ones - complementing and adding new features to the design process.

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TOWARDS STATISTICAL SIGNIFICANCE OF CONFIGURATIONAL MODELS:

New evidence of variance and bootstrapping

JOÃO PINELO SILVA
Department of Architecture & Interior Design, University of Bahrain, Kingdom of Bahrain
jpinelo@uob.edu.bh

ABSTRACT

Configurational modelling involves simple but powerful methodologies that seamlessly integrate the design process and has high adherence by professionals. However, a traditionally intuitive approach, rather than a statistically informed one, occasionally compromises such models. As a consequence, the models often do not reach statistical significance and therefore are of limited efficacy. Were they to reach statistical significance, configurational models would increase their validity but also the potential for data sharing and therefore their economic feasibility. In this paper, I discuss the aspects of the process of creating configurational models that are crucial towards statistical validity. After introducing the methodological framework, I focus on the two stages for measuring traffic: finding a representative sample for each spatial unit and measuring sufficient units to form the model. I present new evidence of the expected variability of data that dismisses common but false assumptions that often lead to statistical insignificance. I demonstrate how the introduction of variance breaks down a model. I argue that reaching statistical significance can be achieved with the use of basic statistics, which are within reach of designers. Finally, I introduce Bootstrapping, an advanced but straightforward method to provide statistical significance in cases of a small sampling.

KEYWORDS

Space syntax, configurational models, spatial configuration, covariance analysis, bootstrapping.

1. INTRODUCTION

According to Karimi (2012), the configurational approach, "... provides a reliable evaluation system that can lead the design process by bringing together creativity and research into a single framework." (Karimi 2012, p. 299). Perhaps this is part of the reason for its wide acceptance by planners and architects. Often, such studies are used by professionals to 'get a grasp' on the role of the configuration in social and economical phenomena.

Observing social dynamics within a spatial framework is rooted in the architectural tradition through the works of some of the greatest thinkers, who advocate direct observation as a way to understand city life. Examples are the works of Jacobs (1961), Alexander (1977, Alexander 2002), Whyte(1980, Whyte, Whyte 1988), Hall (1980, Hall 1990), Lynch (1964), Gehl (1999, 2000, 2006, 2006, 2010). While these authors refer to observation as the means to an intuitive understanding of a place, others, such as Gehl, use more systematic and quantified practices. Gehl and Svarre (2013) compiled a list of methodologies for the observation and measurement of behaviour and traffic. Architects and planners often extend the approach to model pedestrian and vehicular traffic, by linking configurational properties to traffic volume. However, this is sometimes done in an intuitive way, following tradition, rather than a statistically sound

methodology. As a result, the models may lack statistical significance, and therefore their use may be limited.

Architects are no longer the exclusive drivers for the systematic consideration of pedestrians in planning. Non-motorized counts are a key element in calibrating multimodal models (Ryus 2014, p.19), therefore, suggesting opportunities for data sharing between architects, planners and 'traditional' transportation modellers. Pedestrian and cycling data tend to be used for several purposes simultaneously (Ryus 2014, p.86). A practitioner survey identified the lack of staff time and funding limitations as the most common barriers to collecting more non-motorized traffic data (Ryus 2014, p.25). Lack of sufficient counting data is a limitation of configurational-based models. However, in a context of wide interest for such data, the lack of resources may be overcome by cost-sharing. Data sharing would imply statistical significance, which in this context, is a new concern for architects, and hence worth covering now.

The paper focuses on the less-documented aspects of data management and sampling issues, which, for the benefit of a broader audience, can be addressed through basic statistics. Firstly, I briefly describe the configurational approach; secondly, I discuss covariance analysis and the issues of spatial distribution and temporal aggregation of data. Thirdly, I present new evidence of the variance of pedestrian traffic and demonstrate the potential negative impact of the large variance of flow on models. Fourthly, I discuss the procedure for sampling statistically significant traffic data and introduce an advanced method to increase the reliability of small samples; which is followed by conclusions.

2. DATASETS AND METHODS

The configurational approach is based on the analysis of the relationship between network properties of the spatial configuration, such as measures of centrality (e.g integration or choice), and socio-economic phenomena (e.g. traffic or land use).

There is a long history of axial and segment maps being used to model traffic. Reports of significant correlations between traffic and network centrality extend back to the nineteen eighties. An early criticism was that studies conducted in England were geographically bound. While the first major studies did take place in London (UK), several followed from around the world. To name only a few, Peponis et al. studied six Greek cities (Peponis 1989), reporting high correlations in all cases. Read (1999) did similarly in Amsterdam, reporting correlations of 60-70%. There were also studies made in North Africa (Loumi 1988), Brazil (Pereira 2012), Hong Kong (Chu 2005), Seoul (Park 2015), the United States (Raford 2003), and Israel (Lerman, Rofè et al. 2014).

Some of these are major studies, with large samples and statistically significant results. For example, Hillier (1993) measured traffic in 379 street sections. Penn's (1998) study involved pedestrian traffic in 466 locations and vehicular in 397 locations. In both cases, traffic was measured all day, with measurements repeated 20-30 times. In Penn's work, confounding variables were building height, predominant land use and road width. Penn reported correlations between $r = 0.82$ and $r = 0.58$ at $p < 0.0001$ between traffic and integrated centrality measures. Other variables such as land-use, building height and road hierarchy correlated at 0.12, 0.22, and 0.81, respectively. The work by Penn (1998) is of increased relevance because it also reports on a quasi-experimental approach, rather than the traditional purely correlational approach, and thus it has high scientific validity.

The performance of the configurational model can be explained by the hypothesis advanced by the natural movement theory (Hillier, Penn et al. 1993). The theory postulates that asymmetries in the topology of the spatial configuration create unevenness in the accessibility of street segments. Other things being equal, increased availability is likely to result in higher traffic, and land use locates along the network according to this. In turn, land use reinforce traffic patterns.

In most cases, other variables (such as land-use, building height, the number of street lanes, residential and employment density, proximity to public transit, road width, etc.) can increase the performance of the model. However, the cost of including the other variables is often

prohibitive. Traditional transport models use such a variety of inputs and are therefore data and labour intensive, and as a consequence rather expensive to build (Weber 2012). On the other hand, Pereira (2012) observes that even traditional data-intensive transportation models (such as the Atkins Saturn), would benefit from including configurational variable(s).

The creation of a configurational model follows five steps. First, draw the axial/segment map with any CAD/GIS package (or within UCL DepthmapX software). Second, import the map to UCL DepthmapX (or access this directly via Quantum GIS Space Syntax Toolkit (Gil et al, 2015)). Third, compute the centrality measures. Fourth, measure traffic and input data. Fifth, plot the relationships in UCL DepthmapX or statistical package. During iterative sessions, changes to the configuration (edited in the software) lead to the repetition of steps 3 and 4.

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2.2 COVARIANCE ANALYSIS

Covariance analysis is a statistical method used to check if two variables are associated, which is at the root of configurational-based models. Essentially, it analyses the covariance of the variables, as in do higher values of variable A correspond to higher values of variable B, and lower values of variable A to lower values of variable B - a positive correspondence - direct relationship. Or the opposite - inverse relationship. If the variables show consistency, then values of the dependent variable can be extrapolated from those of the independent variable. Typical independent variables are descriptors of the built environment, such as land use, building height, and measures of network centrality, among others. The dependent variable is (typically) measured traffic.

The strength, or magnitude, of the relationship, is the correlation coefficient (r). A strong relationship[1] is said to be of high covariance, with the value of r approaching 1, while 0 represents the absence of a relationship. The sign describes the direction. A positive r implies a direct relationship, while a negative r implies an inverse relationship. For the purpose of interpretation, it is more useful to calculate the coefficient of determination R2 (R2 = r2). R2 represents the variability shared between the two variables.

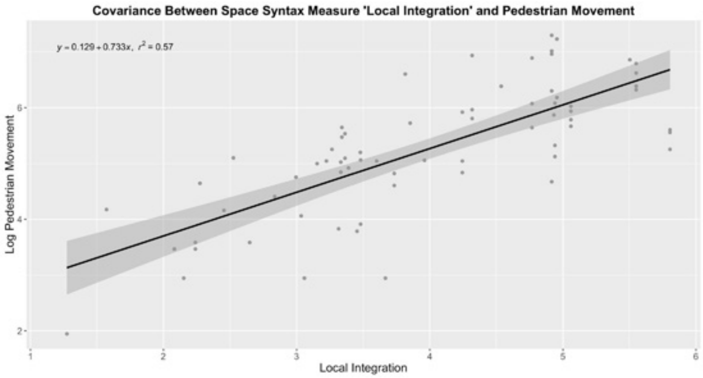

Figure 1 - Correlation and r2 between centrality measure 'local integration' and measured pedestrian traffic for the South Kensington Museum area in London.

The relationship of covariance is typically visualised through a scatterplot (as in Fig. 1), where the x-axis and the y-axis represent the independent and the dependent variables, respectively. Each point represents a spatial unit (street segment). Fig. 1 illustrates a positive correlation between two variables. Without implying a causal relationship, R2 suggests how much of the variability in local integration is shared by the logarithm of pedestrian movement (I explain the reason for using the logarithm of the measurement below). R2 can be multiplied by 100 to obtain a percentage. One can read the result as: local integration can account for 57% of the variation of the logarithm of the pedestrian movement; which implies that 43% of traffic cannot be explained by local integration alone. Notice that for the coefficient of determination (R2) of 0.57, the correlation coefficient (r), = $\sqrt{0.57} = 0.75$. R2 is a measure of the substantive importance of an effect, not simply the correlation coefficient.

Though the values of r and R2 represent the magnitude of the correlation and can safely be interpreted as mentioned above, this, per se, does not mean that, statistically, the covariance is significant. One can only measure the statistical significance of r by testing a hypothesis; which is done using probabilities. The hypothesis to test is: what is the probability that the correlation is different from zero? In statistical terms, this is called the null hypothesis. Statistical packages

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[1] Cohen (1988, 1992) suggests 0.5 and larger as a large effect.

do this and present the result as the p-value, which is a measure of the weight of evidence against the null hypothesis. The universally accepted value for declaring statistical significance is over 95%. Therefore, confirming the null hypothesis requires a likelihood > 95%. Consequently, not confirming it requires < 5%. Therefore, the threshold value of p is < 0.05 (0.05 probability or < 5%). In the example of Fig. 1: R2 = 0.57, p = 4.825e-14 (or 0.00000000000004825), and therefore $p \leq 0.001$[2] (statistically highly significant); this means that the probability of the null hypothesis (meaning absence of a relationship) is less than 5%.

Conceptually, it is important to understand that, statistically, this is not a confirmation that the relationship exists. It only means that it is extremely unlikely that it does not exist. Since one cannot know the statistical significance of the effect measured without the p-value, this should always be reported. The R2 and p values are as important as the scatterplot itself. Without these, one cannot be confident that the 'cloud' of points follows the correlation line. Urban planners often use scatterplots as quick diagnosing tools. By identifying outliers, practitioners immediately flag places that are underused or overused about their 'natural' configurational potentials. This flagging system turns out to be rewarding because these points concentrate high potential for improvements. I have often seen little additional local analysis yielding a high level of objectivity for 'surgical' interventions.

Having analysed variance and measured a moderate to high R2 (> 0.3) with acceptable significance ($p < 0.05$), it is legitimate to use the linear model fitted to the correlation to predict values of y based on x. To do that, one can use the equation of the model (as in the top left corner of Fig. 1). Such process is called regression; it implies working backwards using the model fitted to the data. Regression can be used to estimate (within the probability framework of the model) the amount of traffic on a new street.

The calculation of the correlation coefficient must take into account the type of distribution of the data correlated. For normally distributed data, or large samples, Pearson's correlation coefficient should be used. For not normally distributed data (or for ordered variables), then one should employ Spearman's correlation coefficient. In cases of small datasets and many tied ranks, Kendall's tau correlation should be measured.

Factors to consider when selecting sites to make measurements are: a) choose sites that are at both extremes of the centrality measure, b) add some randomly selected sites, c) include places within the area of the project, and d) include control locations (sites outside of the scope of the project). For how many sites should data be collected? As for any sampling, the principle is the more data, the better. On a more descriptive note, I suggest following the rule of thumb from Green (1991), which basis the recommendation on the number of predictors (k) involved. To test only the R2, the author recommends a minimum of 50 + 8k sites; to test the individual predictors, 104 + k sites. Alternatively, Miles' (2001) suggestions could be followed: a minimum of 30 places for a large effect ($r \approx 0.5$)3 and one predictor, and for a medium effect ($r \approx 0.3$), 60 sites. The numbers increase for more predictors. Smaller effects ($r \approx 0.1$) would require a minimum of 400 sites for one predictor.

2.3 SPATIAL AND TEMPORAL AGGREGATIONS OF DATA

Models of pedestrian movement try to discern regularities in the spatial distribution of a population. They focus on relationships between phenomena on the basis of their location; that is, phenomena are assumed to be related because they co-exist geographically.

A brief analysis of the spatial distribution of traffic data makes it obvious that the movement of population is not evenly distributed. Rather, it is asymmetrically distributed (positively skewed), with the majority of places having comparatively little circulation and very few places having much larger quantities of movement, resembling a logarithmic frequency distribution (Fig. 2). This asymmetry is relevant because to measure the covariance between variables it

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[2] The American Psychological Association (APA) recommends that the exact p value be reported, unless this is < 0.001, in which case it should be reported as such (APA, 2010). Note that $p < 0.001$ means rejecting the null hypothesis at a 99.9% confidence level. That is, that there is less than 0.1% chance that the null hypothesis is confirmed.

is important that they follow a similar pattern of distribution. Because the centrality measure of integration approximates a normal distribution, the traffic variable is transformed towards a normal distribution through the application of a logarithmic transformation. Therefore the logarithm of traffic is plotted in Fig. 1. Data transformations such as this are common procedures in mathematics (Games 1984). Fig. 2 illustrates the frequency distribution of the raw values of movement (left) and integration (centre), as well as the effect of the log transformation of movement (right).

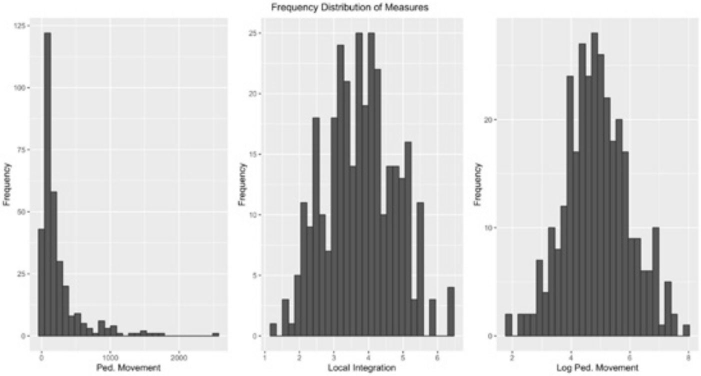

Figure 2 - Left: variable pedestrian movement follows a logarithmic distribution. Center: Local Integration follows a normal distribution. Right: the log transform of pedestrian movement follows a normal distribution.

While the features of the built environment are relatively stable, the flow of movement on the spatial unit empirically varies over time. Therefore, the value that represents the traffic variable is the result of a time-wise aggregation of circulation in that spatial unit. As Fig. 1 illustrates, each point on the scatterplot is represented by one value of y. It is, therefore, necessary to find the one value that describes the overall traffic in each spatial unit. Traditionally this is the mean of the hourly traffic measured throughout the day, as in (Penn 1998, p.70). Stage two is to collect data on enough spatial units to reach statistical representativeness for the overall model. Stage two was explained above; stage one is discussed below.

2.4 MEASURING PEDESTRIAN TRAFFIC

Time-cycles that are empirically observable (e.g., daily and weekly) seem to be seductive regularities that researchers might be tempted to lean on to discard the need for repeating measurements. However, as will be demonstrated, these time-cycles are not as numerically regular as one would infer by simple observation. Therefore, relying on them would compromise the statistical significance of the model. Nonetheless, even when faced with large differences in measured volumes, researchers often dismiss the need for further measurements. The dismissal of the variation is likely to originate with the uncertainty generated by the whole process, where data tell one story, but observable daily patterns seem to suggest another. Furthermore, because traffic is sampled, the differences in measurements can be interpreted as the result of the interpolation process rather than an actual variation of flow. Furthermore, the traditional data collection process, conducted with pen and paper annotations with quick sums on site and posterior data input to spreadsheets, has itself abundant opportunities for data management errors. Overall, the only assumptions made must be very basic or broad, and directly confirmed within the data. These might involve such things such as the shape of the frequency distribution of a population or samples.

In statistical terms, the problem of stage one is one of creating samples to represent a population. The first step is to define the population, which would be the number of pedestrians who move through the spatial unit within the timespan that one aims at characterising. To portray one day of traffic, for example, measurements should be repeated on 30 days. The repetition implies the statistical notion of sampling. The statistical aspect implies the Central Limit Theorem (CLT) (Feller 1968, Feller 1971), which, in simple terms, postulates that given sufficient measurements of a phenomenon, their distribution tends to be normal. This is significant because the properties of normal distributions are well known. Therefore, demonstrating that the distribution of the samples tends to normality makes the inferences made from the samples to the population well documented, not only regarding specific values but critically also for the margin of error. There is a certain agreement among statisticians that "enough measurements" is approximately 30 (Field, Miles et al. 2012, p.43). With a smaller number of samples, it is likely that normality might not completely reveal itself; therefore, for smaller samples, a t-distribution must be assumed.

For explanatory purposes, I am assuming measuring 30 'typical weekdays', which (to me) begins to be reasonable from an ethical standpoint as it gains statistical validity. For example, to characterise weekdays, one would take measurements on different weekdays (30 in this case). To describe one particular day, e.g., Wednesdays, then 30 Wednesdays should be measured.

Another issue to consider when planning counts is how long to count for, since typically it is not possible to count for the entire period of interest. As a matter of principle, one could assume that the longer the sampling time, the more reliable the count. As reported by Turvey (1987), this direct relationship is the case only up to a certain threshold, after which the increase in time does not provide a proportional increase in reliability. Turvey's data suggest a minimum of ten minutes for sampled counting. However, in low traffic areas (especially where zero counts could be recorded) longer periods should be used. Counts for smaller periods are often used to infer hourly rates. This is done either by using a blind expansion factor (e.g. six for ten-minute counts), or one based on locally measured data. Despite their common use, expansion factors imply error and should only be used if absolutely unavoidable. For more on this practice see Turvey's (1987) comprehensive study. Hankey (2014) discusses scaling factors.

In statistical terms, one measurement of the variation of a sample is the standard deviation (SD), which is an indication of how well the mean (as a model) represents the population. A large SD indicates a large variation from the mean and therefore using the mean to represent the population may imply a significant misrepresentation. A small SD suggests otherwise. If one collects several samples, the measure to which the mean of the sample means represents the mean of the population is the standard error (SE). In general terms, it can be stated that:

$$\text{Outcome (inferred population)} = \text{model} + \text{error}$$

If the mean is the model, then the error is the SD, and therefore:

$$\text{Outcome} = \text{mean} + \text{SD (or SE}^{3}\text{ as described above)}$$

Knowing the nature of the curve of the distribution of values of a sample is critical when assessing the quality of fit of a model. It is known that, for a normal distribution, 99% of the samples of a population will have their means within ± 2.58 times SD. For a 90% confidence level (CL) this factor is 1.64. The mean plus and minus these factors provide the upper and lower boundaries of the confidence interval (CI). A larger CI range implies a less good fit of the mean to represent the population.

Representing the CI can be done numerically or graphically, as per Fig. 3, which displays error lines and the counts as points. This example includes some equivalent-hour combinations that have been counted only once per gate (for example Friday at 14 hours). Notice that in such cases, the mean coincides with the count, but crucially, there are no error bars. The absence of such is a sign not of the lack of error, but of the insufficiency of data to estimate the error.

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[3] As previously mentioned, if using the means of several samples, the standard error should be used rather than the standard deviation.

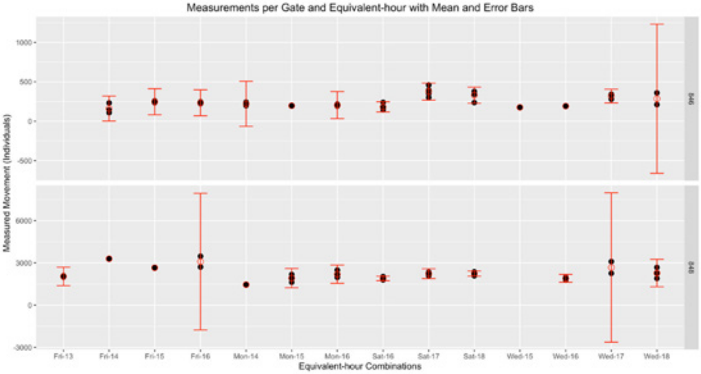

Figure 3 - Count data per equal-hour combination, grouped by gate (846 and 848). Black circles represent count values (three solid circles per equivalent-hour per gate mean that three counts were made. The value of each count can be read on the y axis.). Circumferences represent the means of counts. The lines represent the error for a 95% CL, i.e., the range of the CI for the 95% CL.

3. VARIABILITY OF MEASURED FLOW

Despite several studies referring to pedestrian counts, the perspective is traditionally one of reporting the data and not informing the methodology. One exception is a study by Turvey (1987) focusing on the method of counting and sampling. The study explores data of 15 locations in the United Kingdom to find an ideal sampling duration. The method implied full-time counts for the stipulated periods and an analysis of the variation of different sampling periods from five to forty minutes in five-minute increments. The variation between samples of the same time-span within the same counting interval was as high as ± 50% in the pilot study and reached 40.2% in one case of the main study. Even with the recommended sampling length of 20 minutes, Turvey (1987, p.24) concludes "a coefficient of variation of at least 25% must be assumed".

The considerations about pedestrian counts do not stop with their inherent variability within a particular period. The same study reports that when comparing twenty-minute sample volumes for two different days, each for three periods (for eleven sites, mostly on various weekdays) the highest error measured was -59% (Turvey 1987, p.40). The mean of the absolute values of the error was 48%; the minimum error was 0% and the mean of the absolute error 18.24, with a SD of 16.72. These values suggest a significant variation between movement volumes for different days at the same site and time of observation. The finding seems to defy a common assumption: that traffic at one site repeats itself in precise daily cycles.

Turvey's study reports changes in the same period in several days, but not necessarily the same weekday. Therefore, it is not absolutely conclusive that variation exists among equivalent time periods, i.e., the same weekday at the same time, henceforth called equivalent-hours. A dataset of counts made at two sites in the Kingdom of Bahrain during January and February 2015 can help to clarify this point, as it provides evidence of the variance of measurements within equivalent-hours. The Bahraini dataset does not contain sampling but 57 continuous hours of observations in 20 combinations of equivalent-hours in two sites at different times of the day and on different days of the week. The analysis reveals that measurements of equivalent-hours (taken in the same place on consecutive weeks for the same time-period) yield different results, with considerable variation. Table 1 summarises the results.

Gate ID	Weekday	Hour	N	Week Diff.	Min.	Max.	Mean	SD	% Diff.
848	Wed	16	3	4	1778	1992	1903.33	111.61	7.71
848	Wed	18	3	3	1896	2678	2277.33	391.36	24.17
848	Wed	17	2	2	2258	3092	2675.00	589.73	21.92
848	Fri	13	2	6	1987	2090	2038.50	72.83	3.40
848	Fri	16	2	6	2706	3470	3088.00	540.23	17.20
846	Fri	14	3	6	108	232	161.00	63.93	55.36
846	Fri	15	2	6	234	260	247.00	18.38	7.14
846	Fri	16	2	6	221	247	234.00	18.38	7.55
848	Sat	16	4	4	1792	2028	1893.25	98.29	8.41
848	Sat	17	3	2	2079	2350	2234.33	139.79	8.33
848	Sat	18	4	4	2084	2364	2237.25	115.39	8.57
846	Sat	16	4	4	145	239	181.75	40.26	35.54
846	Sat	17	4	4	301	459	376.25	67.67	29.78
846	Sat	18	4	4	236	378	330.25	64.70	33.41
848	Mon	15	3	3	1627	2176	1914.33	275.40	20.22
848	Mon	16	3	3	1971	2486	2201.00	261.87	16.02
846	Mon	14	2	2	198	243	220.50	31.82	14.08
846	Mon	16	2	2	191	218	204.50	19.09	9.00
846	Wed	17	3	3	279	342	319.00	34.77	14.00
846	Wed	18	2	3	211	360	285.50	105.36	38.11

Table 1 - A summary of the differences in measurements between the twenty equivalent-hour combinations. N is the number of weeks that particular combination was measured; Week Diff. is the number of weeks between first and last measurements; Min. and Max. are the min. and max. values measured, respectively; Mean, SD and Var. are the mean, standard deviation and variance of the measurements, respectively; % Diff. is the percentage difference between the minimum and maximum values.

If the SD is not sufficiently intuitive as an indication of the variability of the data, I include a column with the maximum percentage difference (% Diff.) registered for each equivalent-hour (row). Note that this is not exactly equivalent to SD because it involves only the minimum and maximum values, unlike SD, which comprises all values and their distances to the mean; however, the value as a percentage might provide a more intuitive measure of the range of variation observed. The summary statistics for percentage difference (% Diff.) are as follows: Min. 3.4%, Max. 55.36%, Mean 19.00% SD 13.49%.

The variability of measurements reported suggests that such variation should be expected between measurements in the same place, at equivalent-hours. However, because not all cases were measured the same number of times (between 2 and 4, column N in Table 1), it was plausible (though not likely) that the variation was a function of the number of measurements. A simple correlation suggests no such relationship (Fig. 4). As Fig. 4 and the r2 of 0.068 suggest, the number of times each equivalent-hour was measured does not seem to influence the percentage difference.

In summary, the case study strongly suggest that a high variability between counts of the same phenomenon is to be expected, whether on consecutive days, or equivalent-hours, thus disproving the myth that movement repeats itself in precise daily cycles. The findings also suggest that the distribution curve of samples will be wide, tending to platykurtic, with large standard deviations. These findings imply: a) high variability encourages the use of extensive sampling, and b) when using the mean for a model, one must disclose the error of the distribution, quantified by SD or SE.

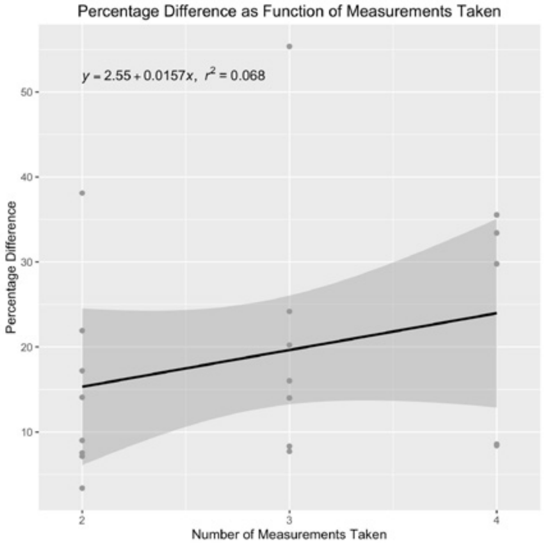

Figure 4 - Scatterplot of the covariance between the number of times each equivalent-hour combination was measured and the percentage difference between the minimum and maximum values. The shaded area represents the 95% CI around the regression line.

3.1 THE POTENTIAL IMPACT OF LARGE VARIATION IN MEASUREMENTS

The wide variance strongly suggests that a reliable account of the traffic that is representative of a place must reflect several repeated measurements. To illustrate this point, I use a benchmark dataset (Jiang 2009) for configurational models. I adopt it for its public availability (at http://discovery.ucl.ac.uk/1232/), and the fact that it has been extensively studied (Carvalho and Penn 2004, Hillier and Iida 2005, Jiang 2009). It contains centrality measures and traffic for four London areas: Barnsbury, Brompton, Calthorpe and South Kensington Museum. The areas were originally chosen to include a "range of different predominant land use types and mixes, densities of development, and street grid morphologies." (Penn et all, 1998, p.63). All present highly significant correlations between traffic and local integration (Figure 5). The traffic data was gathered through 20-30 repeated measurements, and the four areas have R2 of 0.66, 0.45, 0.59 and 0.57, respectively, all at $p < 0.001$ (left column of Fig. 5). The scatterplots in the right-hand column of Fig. 5 represent the correlations with hypothetical (synthesised) data based on the multiplication of measured values by a random factor based on the percentage difference found in the Bahraini dataset (a random normal distribution with mean = 18.99709 and SD = 13.49427). As a result, the R2 decreases, simulating the potential results of a less-well-documented measurement.

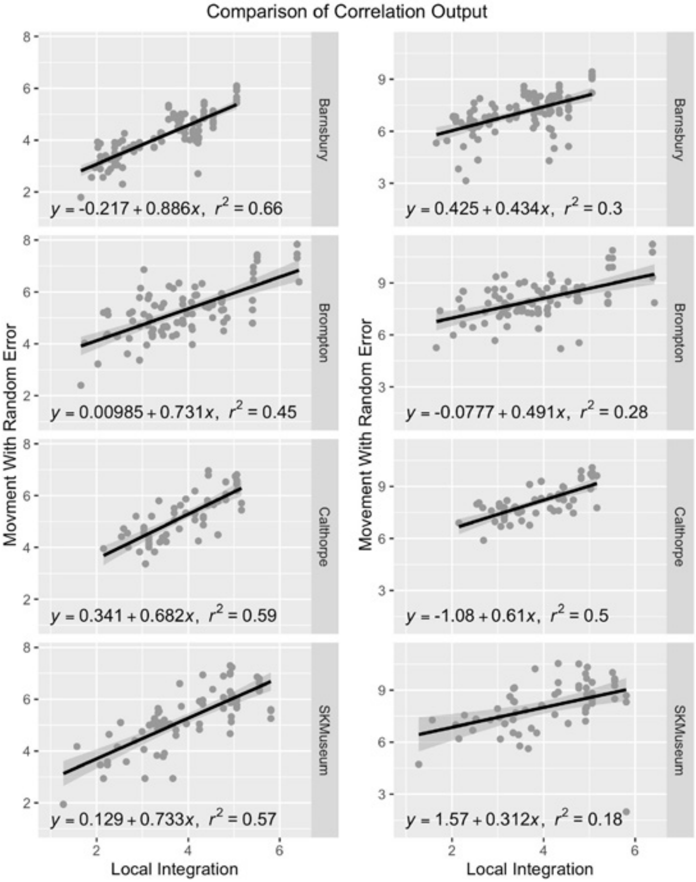

Figure 5 - London dataset. Correlation and r2 for the four London areas. Real values are on the left. On the right are synthesized data based on real traffic but altered by multiplication by a random normal distribution with mean and SD as reported in the study in the Kingdom of Bahrain. Note the shaded areas around the regression lines; they represent the 95% CI.

One can argue that a high R2 achieved between such variables (as centrality measures and traffic) represents a high level of order that is phenomenological relevant; implying that the traffic values have 'captured the essence' of circulation through the network. Such argument would be a reasonable assumption; after all, notice that with syntactic data (Fig. 5), none of the initial correlations improved when randomness was introduced. Nonetheless, if the supporting data are not statistically significant, then the assumption might be invalidated.

4. SUGGESTIONS FOR REACHING A REPRESENTATIVE MEASUREMENT

The mean of the population is inferred from the mean(s) of the sampled movement. The inference implies uncertainty, and therefore a confidence level (CL). To measure the confidence interval (CI), it is necessary to know the shape of the distribution. The relevance of the number of samples is obvious in the formula (1) for standard deviation (similar for SE):

$$s = \sqrt{\frac{\sum (x_i - \bar{x})}{N - 1}} \qquad (1)$$

Where is standard deviation, are sampled values, is the mean of the sample and the number of elements in the sample. As per the equation, a larger denominator yields a smaller standard deviation. One obvious way of achieving this is to increase the sampling (N). The magnitude of the effect depends on the tendency to the mean.

If, despite a sample of 30 counts, the SD is still large, one must accept that the mean is not a good fit for the data, and that should be made clear as an indication of the limitations of the model. This can be shown graphically, as illustrated in Fig. 3, or by calculating the boundaries for a certain confidence level. As an illustrative example, I take a case reported in Table 1 (row 2). The measurements imply that it can be assumed that, if 100 samples were taken, in 99 of those samples the estimated mean of the population would be the mean of the sample ± 2.575 times its SD, or 1903.33 ± 287.40 = 16015.93 and 2190.73, a difference of approximately 575 persons. This is approximately 25% of the mean - this is a CI (also called margin of error) of ± 12.5% (at 99% CL). A lower CL would imply a lower range CI.

Note that with a non-normal sampling distribution (or less than 30 measurements), the boundaries of the CI can be calculated based on a t-distribution. Factors for this can be found in tables that are easy to find in statistics books. To choose the correct factor, one uses the degrees of freedom (DF = N-1). As illustrated by such tables, the higher the DF, the lower the factor, and therefore the narrower the confidence interval for a CL, again highlighting the importance of repeated measurements.

Alternatively, when it is not possible to make 30 measurements per event, a more advanced statistical method can be used to simulate a larger number of samples - Ordinary Nonparametric Bootstrap, or Bootstrapping for short, which can be easily performed with statistical software. Bootstrapping is a resampling technique. It implies repeatedly using the existing samples to simulate new samples. For more on bootstrapping methods please see (Boos 2003).

If one aims at characterising weekly movement at each of the two gates previously mentioned in the Bahrain dataset, one could calculate the mean for each gate based on all the samples available, and use that value on the model. Since the measurements were taken at different times and in different days, it can be argued that they represent the weekly movement. In this case, gates 846 and 848 have 31 and 32 measurements, respectively, and therefore the sample sizes are adequate to, through descriptive statistics only, classify movement on each gate. To illustrate how bootstrapping works, if there were only ten samples for each gate (rather than the 31 and 32 available), one could simulate more by creating bootstrap samples. Bootstrap randomly draws (with repetition) from our ten real samples, for each gate.

Traditionally, this is done thousands of times, and the result aggregated by a statistic, the mean in this case. In other words, rather than calculating the mean of the ten (real) samples, one calculates the mean of thousands of (bootstrap) samples. Fig. 6 illustrates both bootstrapped and non-bootstrapped results for 10,000 simulations (bootstrap samples) for each gate, considering several (3, 5, 10 and 30) initial sample sizes. Note in Fig. 6 that, as the number of 'real' samples increases, so does the 'ability' of the bootstrap to compensate for the lack of data. As Fig.6 suggests, its performance degrades rapidly as the number of real samples diminishes. When bootstrapping is computed, the standard error is also included, and this should also be reported.

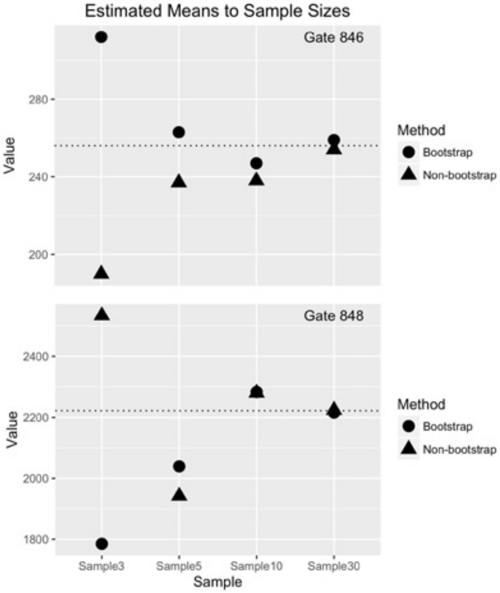

Figure 6 - Plot showing the regression to the mean (dotted lines) of the 32 and 31 samples of gates 846 and 848 respectively. On the X axis, Sample, indicates N number of real samples from where 10,000 bootstrap samples were created. Round markers represent the means of each group of bootstrap samples. Triangular markers dots represent the means of only the N real samples.

5. CONCLUSION

In this paper, I suggest that transforming informal observation methods into formal ones can have a significant impact on the validity of configurational models, which would improve their reliability and widen their usage, and could increase their economic feasibility while expanding the territory covered. I suggest that the minimum threshold for such a transition would be reaching statistical significance. I demonstrate that this is a reachable goal with a resource to basic statistics only, and therefore can be widely applied by designers.

Furthermore I disprove the assumption that traffic flow in equivalent-hours in any one place shows little variability is incorrect, and demonstrate the fallout of a robust model when randomness is introduced by simulating poor traffic sampling. Based on the central limit theorem, I suggest that to reach a statistically significant model, a minimum of 30 repeated measurements are used to characterise a spatial unit. I also suggest several rules of thumb anchored in the literature for establishing the critical minimum number of sites on which traffic is measured. I describe why models should document their limits through disclosing the R2, r, p value, CI and CL for traffic data. Finally, I provide an example of the use of bootstrapping as means to overcome small sampling.

ACKNOWLEDGEMENTS

This work was funded by the Deanship of Scientific Research at the University of Bahrain, grant 12/2014.

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THE SYNTACTIC SIGNATURE OF STARBUCKS' LOCATIONS

Towards a machine-learning approach to location decision-making

JOÃO PINELO SILVA
Department of Architecture & Interior Design, University of Bahrain, Kingdom of Bahrain
jpinelo@uob.edu.bh

ABSTRACT

The space syntax Theory of Natural Movement postulates that everything else being equal, land use selects their location based on the asymmetry of accessibility created by the configuration of the street network. In this article, I test the hypothesis whether configurational (syntactic) properties of an urban street network are relevant for the location of land use. If syntactic features are relevant, then land use types may have a 'syntactic signature'. To identify this blueprint, I apply machine-learning techniques to datasets of syntactic measures, for ten business types. The results are ten models, each with the syntactic blueprint of a type of business. The models are used to predict the existence, or not, of such businesses in segments of the map of London. The performance of the models varies, with fifty per cent reaching statistical significance, including one with 'good' prediction ability. The models for Starbucks coffee shops and solicitor's offices have the strongest prediction ability. The exploratory exercise demonstrates the potential of the machine-learning method Random Forests, when supervised and individually applied to a business activity, to identify the syntactic signature of business types. Such models can be used during planning and design and on location studies. The results strengthen the candidacy of syntactic measurements to location-decision-making. Moreover, they reinforce the theory of Natural Movement.

KEYWORDS

Space Syntax, Land Use, Machine-learning, Random Forest, Spatial Configuration, Urban Planning.

1. INTRODUCTION

One of the toughest challenges of urban development lies between the domains of urban planning and urban design. Practitioners are asked to guarantee that the design is appropriate for the planned occupation. The planner envisages land use, densities, occupancy, and often accepts a layout of the street network. The design of streets and buildings follows, to match the vision. Energy, water, communications, sewage, stormwater, among other infrastructures such as buildings and streetscape, create conditions for the intended land use, expected occupants, and expected traffic. Such arrangements set a stage, but the actors, such as businesses or families might or might not settle in. Understandably, occupancy rates are the first measure of the success of urban development, and demand for a location stimulates the rise in the value of property prices.

The success of a project depends on the suitability of all aspects. Therefore, creating conditions for the planned occupation involves designing with congruence among all infrastructure (Pinelo Silva, 2010). In this article, I discuss the matching of street configuration to land use. This relationship is significant because a mismatch is likely to impair the outcome of the project, in the extreme causing it to fail.

In this exploratory approach, I demonstrate how information extracted from the spatial configuration can be used to inform the planner of the likelihood that an intended specific type of business will locate on a site. In other words, the method can inform the planner of the probability of a match between a type of land use and a place. This knowledge would have advantages. The planners would know, from the design stage, what land use, realistically, they can aim at attracting. It would also permit the planners and designers to iterate the design to maximise the likelihood of success in attracting the desired land use which is important to provide the appropriate design and infrastructure. Furthermore, evidence-based backup of the project might make it more attractive for investors. Space syntax methodologies are already used by practitioners for iterative design with spatial analysis (Karimi, 2012). The work I report here has the potential to extend such approach in depth and facilitate reaching more tangible outputs. I follow the gist of a previous study by Pinelo Silva (Pinelo Silva, 2006), albeit with an entirely different and more robust approach.

The founders of configurational research present the natural movement theory (Hillier, B. Penn, A., Hanson, J., Grajewski, T., Xu, 1993) as the rationale behind configurational models. The theory postulates that other things being equal, the asymmetry of the spatial network creates a hierarchy of accessibility that influences businesses on the selection of location for premises. Contingent on their dependence on footfall, businesses pick locations based on network characteristics such as connectivity, integration and choice at different radii. For example, one business type might benefit from both high global and local integration, while another from great global integration, and low local integration. I use machine learning techniques to identify the pattern of location of ten business types based on the syntactic properties of their current locations in London, UK.

If the natural movement theory is correct, and land use location is dependent on syntactic properties of the configuration, then it should be possible to reverse-engineer the process and find out which levels of each syntactic features a particular land use locates on. In other words, it should be possible to find out the syntactic signature (blueprint) of a business type. To date, there is (to my knowledge) no documentation of the use of syntactic properties in the location decision-making procedures of businesses. Therefore, the process is not literally reverse-engineering, but the uncovering of a hidden order.

Statistical learning plays a key role in science, finance and the industry, often intersecting with other areas such as engineering (Hastie, Tibshirani, & Friedman, 2009b). It is used to ' learn' or identify patterns in data, leading to prediction, identification or estimation of outcomes. I, therefore, apply machine-learning on an attempt to learn the syntactic properties that are common to several instances of each type of business, for ten business types. The syntactic characteristics that are common among all instances of a business type are its syntactic signature, or blueprint.

In a typical machine learning exercise, the dataset is a compilation of the features which are thought to be most promising to inform the classification problem. In the case of business location, this would normally include population data such as density and income, for example. The challenge I take on here is different in the sense that I purposefully limit the dataset to configurational properties - space syntax measures of the segment map of the street network.

2. DATASETS AND METHODS

For this exploratory study, I selected activities that typically have small facilities and are nimble and therefore relocate relatively easily, and are dependent on foot traffic (such as cafes or hair salons) and others that sit on the other end of the spectrum (such as hospitals and primary education). Other business types may lay somewhere between the two extremes. The variety was thought to perhaps lead the way to some classification of land use types as a function of their dependence on configurational properties.

I used the UK's Companies House business database (download 28/02/2016), which contains the registered street address for all businesses listed. I selected the following business types

based on geographic location (Greater London) and on the Standard Industrial Classification of Economic Activities (SIC): Unlicensed restaurants and cafes (SIC code: 56.10/2), hairdressing and other beauty treatment (96.02), hospital activities (86.10/1), specialist medical practice activities (86.22), primary education (85.2), public houses and bars (56.30/2), solicitors (69.10/2) and travel agencies (79.11). It is common practice that some businesses do not operate at their registered address. I, therefore, added two more kinds, not of business types, but branches of brands: Starbucks (the coffee shop) and Waterstones (the bookstore). Both Starbucks and Waterstones make the addresses of their branches available on their websites, from where they were retrieved and stored in a database. The addresses were filtered for removal of branches inside shopping centres as these are not located directly on the street and therefore do not have direct syntactic properties. The addresses were geocoded, and point events created using Google Maps API in Quantum GIS (QGIS). After geolocating, businesses for which addresses were not found, were excluded from the dataset. The events were overlayed on the segment map of London (Source: Space Syntax Ltd), which had been previously analysed with UCL Depthmap X. After this operation, businesses which were located further than 50 meters from the closest segment were eliminated from the dataset. The representativeness (number of events) of each business on the dataset as analysed below are: cafes- 1,669; solicitors- 1,089; hairdressing- 2,033; hospitals-1,208; pubs-973; specialist medical pracice-953 ;primary eductaion-392; travel agencies- 1,059; Starbucks- 157; Waterstones- 26.

The segment map, where each segment was classified as containing or not an event, was imported into R (R Development Core Team, 2016) for analysis through machine-learning algorithms. Overall, the map dataset contained 455,928 segments, with nine variables. The variables, also called modelling features, were chosen based on the two foremost types of measures, often found to correlate with social and economic phenomena (Hillier, B. Penn, A., Hanson, J., Grajewski, T., Xu, 1993; Lerman, Rofè, & Omer, 2014; Penn, Hillier, Banister, & Xu, 1998). The measure Integration represents the potential for movement towards a place, while the measure Choice represents movement through a place. Each measure is represented by four radii: n (the whole system), 3200, 1600 and 800 meters (approximately 5, 10 and 15 walking minutes), plus one categorical variable that indicates if the segment has each business type or not. The existence of the latter variable can be used to develop a 'supervised' (explained below) prediction model (learner). The learner that later can be applied to predict the location of businesses based, solely, on the eight syntactic features. The data was preprocessed by normalising the four variables of the measure Choice, via logarithmic transformation.

2.1 MACHINE-LEARNING

In this article, I aim at demonstrating how statistical learning can be used to predict if a particular location, whether existing or being planned/designed, is likely to have the potential to accommodate a specific type of business. The aim is to predict the outcome of the question: Is this site syntactically similar to other Starbucks' sites? To which the answer might be either 'yes' or 'no'. The first meaning that the location has syntactic features that are similar to the current locations of Starbucks shops, and therefore has the potential to host a Starbucks shop; and the latter meaning the opposite. In this case, there are two possible outcomes (two classes): i.e. 'Starbucks' and 'no-Starbucks', therefore the problem is one of binary classification.

As in a typical machine-learning scenario, I start with an outcome variable. In this case, a categorical variable of the existence or not of one business type for each map segment. Since the method is based on the availability of known outcomes, this is a supervised learning process of classification. (In comparison, an unsupervised process would classify into classes which were not previously defined.)

A fundamental part of a model is a measure of its performance. Performance should not be measured on the same dataset that was used to make the model, as this would not reflect the ability of the model to predict on new/different data. To have a testing set to measure the performance of modelling output, I randomly divide the initial data for each business into two independent datasets. The training set, with 75% of the events; and the testing set, with 25% of events. The split is done via random subsampling, without replacement. Therefore, independent

training and testing sets are created for each business type. The training set is used to 'observe' (learn) the outcome based on features, the syntactic values. Based on this 'observation', I build the prediction model (or learner). The learner is later used to predict outcomes on the testing set. Since the real classification for the testing set is known, it is compared to the modelled outcomes. I simple terms, the delta between the two reflects the performance of the model.

On an exercise of binary classification, the outcome is two-fold: event belongs to class, or event does not belong to class, such as in 'Starbucks' or 'no-Starbucks'. When assessing the performance of the output of the binary classification, the results can be grouped into four types. True positive = correctly identified as belonging to the class; false positive = incorrectly identified as belonging to the class; true negative = correctly rejected as not belonging to the class; false negative = incorrectly rejected as not belonging to the class.

2.2 RANDOM FORESTS

I used the modelling technique Random Forests (Breiman, 2001) applied to the dataset described above. In the first step of the process, the model is created by using decision trees (Hastie, Tibshirani, & Friedman, 2009a) to 'learn' the syntactic properties of each business type, based on the current classification. On the second step, the learner (model), is applied to classification and its performance is tested.

Random Forests (RF) yield accurate models and are robust to overfitting (Hastie et al., 2009b). The RF model is based on an aggregate of decision trees. By itself, each decision tree is fast but not accurate. To improve the accuracy, RF fits several decision trees to form a model. I used the default value for the hyper-paramenter that establishes how many trees are used, which is 500. Each decision tree uses bootstrap aggregation (bagging), meaning that it is fit to a bootstrap sample of the dataset. Furthermore, the variables are re-sampled at each split (tree branch). The number of randomly selected variables used at each split is defined by the hyper-parameter 'mtry'. Since there were eight variables to train the model (ninth variable is the classification), the default was the creation of 3 'mtry's, at 2, 4 and 6 variables. To maximize the abiity of the model to learn, I induced seven 'mtry's, at 2, 3, 4, 5, 6 and 7. The software simulates learning for each of the 'mtry's and chooses the one with the best performance to create the model.

I used the R packages caret (Kuhn et al., 2012)(version 6.0-76) as well as the package ranger (Wright & Ziegler, 2017) (version 0.7.0) (results reported). I used the latter for speed and convenience since the results were similar to the ones obtained with the randomForest package (randomForest (Liaw & Wiener, 2002)(version 4.6-12)). I also used the packages: rpart (Therneau, Atkinson, Ripley, & Ripley, 2015)(version 4.1-10) and ROCR (Sing, Sander, Beerenwinkel, & Lengauer, 2005) (version 1.0-7) to calculate the probabilities and plot the ROC, with similar results to the previously used packages. I used default settings for all parameters except for 'mtry', as described above.

On a first attempt to find the syntactic signatures for all ten business types, I applied one multiclass model to classify all land use types at once. Such approach resulted in very poor prediction ability. Such performance might be due to some street segments having several different events, or because some business types do not seem to have a strong signature and predict well, as the results shown below suggest.

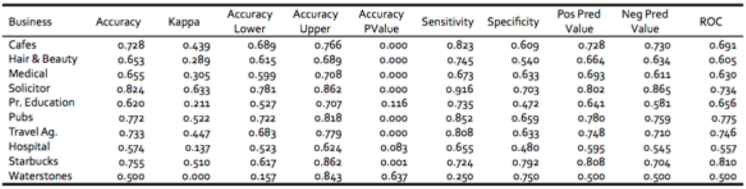
3. RESULTS

Below, I report the results of the models when applied to the testing datasets, which are independent of the training datasets. Therefore, the results discussed and summarised in Table 1 document the ability of the models to make predictions in different datasets, and not how well they predicted on the training data, where models typically show higher performance.

Regarding the overall performance of the model, the simplest measure is Accuracy - the overall proportion of samples correctly predicted by the model. For Starbucks, this was 75.5%, with a p-value of 0.001 at the 95% Confidence Interval (CI). However, Accuracy is a simple measure because it does not account for the possible imbalance of frequency between classes. An

alternative measure, which takes this phenomenon into account, is Kappa. For Starbucks, the Kappa is 0.51, and for solicitors is 0.63. (For reference, values above 0.3 are generally considered as acceptable.)

Other measures of performance can be used to understand specific aspects of the predictive ability of the model. Sensitivity (True Positive Rate, or Recall) is a measure of the proportion of true positives. For Starbucks, Sensitivity is 0.72. Specificity (True Negative Rate) is a measure of the percentage of true negatives. For Starbucks, Specificity is 0.79. The predictions of the existence of a Starbucks shop is correct approximately 70% of the time. The prediction of the absence of Starbucks is correct approximately 80% of the time. These and other values for all ten models are summarised in Table 1.



Business	Accuracy	Kappa	Accuracy Lower	Accuracy Upper	Accuracy PValue	Sensitivity	Specificity	Pos Pred Value	Neg Pred Value	ROC
Cafes	0.728	0.439	0.689	0.766	0.000	0.823	0.609	0.728	0.730	0.691
Hair & Beauty	0.653	0.289	0.615	0.689	0.000	0.745	0.540	0.664	0.634	0.605
Medical	0.655	0.305	0.599	0.708	0.000	0.673	0.633	0.693	0.611	0.630
Solicitor	0.824	0.633	0.781	0.862	0.000	0.916	0.703	0.802	0.865	0.734
Pr. Education	0.620	0.211	0.527	0.707	0.116	0.735	0.472	0.641	0.581	0.656
Pubs	0.772	0.522	0.722	0.818	0.000	0.852	0.659	0.780	0.759	0.775
Travel Ag.	0.733	0.447	0.683	0.779	0.000	0.808	0.633	0.748	0.710	0.746
Hospital	0.574	0.137	0.523	0.624	0.083	0.655	0.480	0.595	0.545	0.557
Starbucks	0.755	0.510	0.617	0.862	0.001	0.724	0.792	0.808	0.704	0.810
Waterstones	0.500	0.000	0.157	0.843	0.637	0.250	0.750	0.500	0.500	0.500

Table 1 - Summary of performance statistics. Accuracy Lower and Upper, as well as p-value refer to 95% Confidence Interval (CI). ROC refers to the area under the ROC curve (AUC).

Other, finer, measures of performance are: Positive predictive value - the probability that there is Starbucks when the model predicts Starbucks; or what fraction of the positive tests the model got right (what portion of predicted Starbucks actually have Starbucks). Negative predictive value - the probability that there is no Starbucks when the model predict no-Starbucks. These measures for all models are available in Table 1.

The trade-off between Sensitivity and Specificity can be visualised on a Receiving Operator Characteristic (ROC) curve (see Figure 1). The area under the curve (AUC) can be used to quantify the quality of the model, where 1 represents the perfect model (no compromise is needed in one measure to improve the performance on the other measure). Typically, values over 0.7 are considered as fair models; over 0.8 are good; over 0.9 are excellent. Starbucks' area under the ROC curve is 0.81.

Another successful model is that of solicitors, with an accuracy of 0.82 (82%) (p-value < 0.001 at 95% CI), sensitivity of 0.92 and specificity of 0.7; with an AUC of 0.73. This model consists of a robust sample with 1,089 events. All models except primary education and Waterstones reach statistical significance with p-values < 0.05 (95% CI). Waterstones has an extremely small sample and is included mostly for investigative and demonstrative purposes. Nonetheless, it represents a worthless model. Note for example it's AUC of 0.5, indicating the absence of the ability to make predictions with success beyond random (50% for a binary classification such as this one). The results are significant since the only variables used in these models are network measures of centrality, while in reality, location studies tipically include socio-demograpfic ones. Furthermore, the measure of Positive Predictive Value shouldn't be expected to perform too well, because the fact that a segment has the right chracteristics for a business does not imply that a facility already exists there.

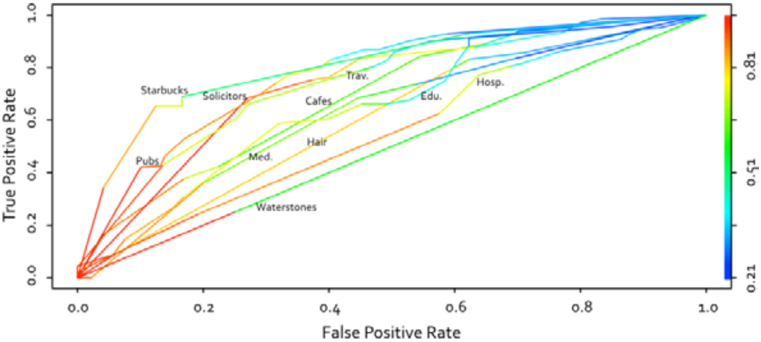


Figure 1 - Illustration of the ROC curves of the ten models. The curve of an ideal model would follow the y-axis from 0 to 1 and then the x-axis from 0 to 1. Starbucks' curve is the one that comes closer to the top let corner of the plot, and therefore have the larger area under the curve, meaning that it has the best tradeoff between sensitivity and specificity.

Further studies could perhaps investigate the differentiation between the strength of the syntactic signature of a type of business and the ability of models to predict their locations. For example, the model for the location of hospitals performs poorly, with and accuracy 0.57 (just above random). However, this should not be read as implying that, at the time of building, the hospitals did not take the configuration into consideration, since the later growth of the urban network is likely to have changed their relative accessibility. Nonetheless, the analysis seems to suggest a hierarchy of dependence on the configuration. Though it would be speculative to confirm the hierarchy itself based on this study alone, such hierarchy might be a useful way for planners to study and classify location dependency.

4. CONCLUSION

In this paper, I test the hypothesis whether configurational properties of an urban street network are relevant for the location of land use. I apply random forest modelling to a dataset of eight syntactic measures to predict the likelihood of location of a particular type of business on street segments. The supervised method was individually applied to each land use. Five of the ten models attempted have a prediction performance above 70%, statistically significant at the 95% CI. The models for the prediction of the locations of Starbucks street coffee shops and of solicitors' offices, in London, were the top performers, with an accuracy of 76% and 82%, respectively, on the testing set (simulating a real-world scenario).

Based on the results, I reject the null hypothesis - that there isn't a relationship between land use location and the syntactic properties of the configuration. Therefore, it seems possible, to some extent, to build a learner for some activities, identifying their syntactic signature. Such blueprints could be used to predict the potential of a street segment to host a business. Furthermore, this can be done since the early planning and design stages, allowing for measurable, outcome-based, design iterations.

Epistemologically, a possible interpretation of the results is that they seem to support the validity of the Natural Movement theory. A clear classification of businesses/facilities that are predictable would be too speculative at this stage, but may perhaps constitute an interesting follow up on the subject. Perhaps a classification of business types or brands based on their dependence on syntactic properties could be helpful to the field of planning, in particular for the branch of spatial decision-making.

ACKNOWLEDGEMENTS

I should thank Space Syntax Ltd. for granting access to the segment map of London for the study.

SUPPORTING MATERIALS

The machine learning process is comprehensively documented, including R computer code and both analytical and final outputs, and is available upon request. I make two documents available: a PDF file (approximately 200 pages), or an execution-able R code as Rmd file with all datasets. The documents make all the technical details available, beyond the most relevant, which are presented in the manuscript.

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#172

AN ARCHAEOLOGY OF THE PRESENT:

Topo-geometric Properties from the Invention of Geometrical Notation to Non-Standard Variation in Architecture and Design

SOPHIA PSARRA
UCL, London, United Kingdom
s.psarra@ucl.ac.uk

ABSTRACT

As digital technologies revolutionise the ways in which buildings are produced there is a growing risk for architecture to become a practice without a theory. Space syntax has contributed to architectural research, through the description of systematic relationships between patterns of use and spatial phenomena. Yet, in the last three decades it has primarily leaned towards a theory of the city[1]. These are studied as the collective products of society that are either self-organising (cities), or operate independently of the agency of their architects (buildings). Yet, from the viewpoint of architecture as a social discipline, there is a need to describe buildings and their relationship to the city not simply as the emergent products of society but also as products of design. This type of study requires theories and tools that describe topo-geometric properties, or the interaction of spatial with geometrical patterns. It also needs to combine historical research with morphological analysis. In this paper I explore the relationship between topology and geometry through three key periods of Western architectural production: first, the classical invention of geometric notations in architectural drawings; second, the shift of emphasis by modern architects to movement and visual information, freeing architecture from constraints of axial geometrical planning; finally, the end of geometric and notational limitations on the variability of forms with the rise of digital technology. Rather than providing a comprehensive account of architectural design, this paper aims to understand the morphological traditions from which contemporary architectural spaces and forms derive. I argue that as much as space has been a silent instrument in architectural discourse, so has geometry been a silent conductor in Hillier and Hanson's theory of spatial configuration. Aside to tools for topo-geometric analysis, we need theoretical accounts of the ideas we 'think with', bringing space syntax and contemporary architecture into the historical and morphological tradition.

KEYWORDS

Geometry, topology, movement, visibility, non-standard variation, algorithmic design

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[1] Buildings are also studied using space syntax theory and tools but no systemic understanding of buildings exists across a wide range of building types. Further to this, the study of buildings has moved away from the early attempts to build an internal theory of architecture through a clear understanding of the difference between architecture and building. As such, seen from the perspective of architecture, most building studies using space syntax fall into the realm of the normative, recycling old concepts and methods of analysing.

1. INTRODUCTION: THE INVENTION OF ARCHITECTURAL NOTATION

Geometry was always present in architecture but the conscious employment of it goes back to the Renaissance, where through intensive studies of ancient structures and influential patronage, architects, such as Leon Battista Alberti, Sebastiano Serlio and Andrea Palladio established architecture as a discipline separate from artisanal inherited traditions. The purpose was to raise it to an intellectual activity, conversing with learned men, poets, philosophers, and literati. Alberti advises architects to conceive the design in the mind, and revise it many times before building. Once revisions finish nothing should be altered for the better or the worse (1726). Alberti produced the first architectural treatise of the Renaissance, but it was un-illustrated and written in Latin. It was Serlio (1475- c. 1554) who pioneered the use of high quality illustrations to supplement the text, which was written in Italian (1611). Illustrations and the discovery of the press spread the influence of these books in the Western world. While previously architects had to travel in order to study ancient ruins, books brought to them the treasures of antiquity in an illustrated volume. Particularly pocket size books, like Palladio's guide book to the ancient sites of Rome, helped spread classical architecture and paved the road for its revival.

More importantly, it was orthographic projection, the use of techniques to survey existing fragments and generate plans, sections and elevations that led to the design of classical buildings. Until the emergence of digital architecture in the late 20th century, orthographic projection has been a method of representation in drawings and books, a tool for collecting data about buildings and finally a method of design. Raphael described the method of surveying and designing through scaled drawings as follows: *'...you should draw always measuring everything with the scale, and use a line that equals the width of the base of the entire building. From the central point along this line, draw another straight line that makes on either side two right angles; this will be the centre line of the building. From the two extremities of the width line draw two parallel lines, perpendicular with the base line; these two lines should be as tall as the building is to be. Between these two lines, which make the height, you should then measure off the columns, the pilasters, the windows and other ornaments drawn on the front part of the building. And do all this always drawing the lines from every single extremity point of the columns, pilasters, openings, or whatever else, such that these lines are parallel to the lines at the extremities'* (Hart and Hicks, 2009: 186).

Rafael further goes on to describe how the elevation (exterior wall) and the section (interior wall) are derived from the plan. Corresponding parts are joined with parallel lines, which are the conservers of true measure. These lines are considered to be representations of light paths with the source set at infinite distance. *'...the interior wall shows the inside of the building – half, that is, if cut down the middle....In short, with these three orders or styles, it is possible to consider in minute detail all the parts of any building, inside and out'* (ibid.). This method of drawing was essential for the building to be constructed on true measures. But it was also the method that created space. As Robin Evans explains: *'...architectural space would remain, one way or another, limited by and bonded to the pictures that normally gave access to it...projection was an extra ingredient grasping more or less cautiously at the imaginary space behind the three drawings...'*. Evans continues: *'if the side you see is the mirror image of the side you do not see – if, that is, the building is symmetrical about the sectional plane – you see it all through one cut...Vertical, bilateral symmetry is economical within the confines of the technique...A centre line projected through the cavity easily converts into a processional axis. Then the axial route will show up on the principal elevation as a principal entrance, thereby converting the simple, binary equality of left and right sides (a-a) into a tripartite, therefore hierarchical, centralised symmetry (a-b-a)...This is why in most classical architecture design and building are in a near perfect accord'* (1995: 118-119). Another way of saying this is that the building as three-dimensional physical space was an identical scaled copy of the design (Carpo 2007).

2. IDENTITY: ISOMETRIC INVARIANCE BETWEEN DESIGN AND BUILDING

The invention of geometrical notations provided - like an analogue algorithm - instructions for producing a building, as well as for experiencing it from the inside. We can illustrate this

by looking at Palladio's Villa Rotonda (figure 1). The most integrated positions in the Rotonda are situated in the circular hall, drawing to themselves pathways and views through the entire building. All systems of spatial relations, such as physical elements, lines of movement and sight obey the same laws of invariance. All registers of symmetry correspond with each other so that when viewers move in the villa, geometry conditions their vision, movement and appreciation of the relationships between the parts and the whole. The transformations of visual fields, expressed by the way in which the angles and radials of visual polygons (isovists) change from space to space are symmetrical along the axes of movement. At the same time, views are symmetrical from symmetrical positions (figure 1). Aligning the geometrical axes with the processional axes, as Raphael advised, has the effect of geometrically controlling the variability of views, so that the whole building can be experienced as a stable image.

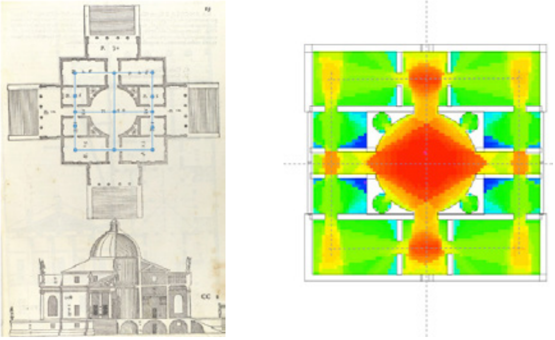

Figure 1 - Villa Rotonda, graph (left) visual integration (right)

Group theory is the branch of mathematics that describes symmetry as the properties that remain invariant under a transformation. In terms of geometry, the Rotonda has six symmetry transformations: reflection on two axes, and rotation on 90, 180, 270 and 360 degrees. In terms of graph structure, the four entrances are symmetrical to each other with respect to the central hall, and the outside, while each of them is asymmetrical in terms of their relationship to the central space; the spaces next to the entrances are symmetrical to each other with respect to each entrance, and so on. Geometrical symmetry and graph symmetry therefore, have the same registers of invariance, creating an isometric correspondence between the building and the design.

Palladio was aware of the difference between built forms and designs, manifested in his exceptional capacity to respond to site and functional problems with elegant solutions (Ackerman 1966). This is evident in his project for a pallazo in Venice in comparison with an ancient house he published in his Four Books, or his *Teatro Olimpico* seen alongside the Roman theatre by Vitruvius (Palladio 1570). Both designs were adjusted to the irregularity of the site conditions. Yet, in *Four Books* Palladio presented an idealised view of architecture, eliminating all adjustments of size and proportions necessary to address the realities of the physical fabric. This marked difference was in effect an outcome of the erudite climate of the period. Architects had to demonstrate to their learned patrons that they practiced architecture as liberal art, concerned with the abstract comparative understanding of architectural types, mathematics and proportions, and not as mechanical art without erudition. The ideal geometries of Palladio in his *Four Books*, demonstrate that he must have followed Alberti's advice to architects, arguing that the design, in essence an informational model, was the product of the author conceived in the mind. The building on the other hand, was an identical copy of this product. In artisanal practices it is the other way around. Artisans and craftsmen 'inherit' 'designs' from existing building practices that survive the test of time and by word of mouth.

If the Renaissance artefact was designed as a microcosm of the universe, and the universe had mathematical origins (Wittkower 1971), the architectural creation had to provide the union between mathematics and the world of the senses. Identity is a special property that defines a symmetry group in mathematics, where a thing can be superimposed upon its image through an isometric relationship of sameness. The classical system of notation established a relationship of identity - or sameness - between geometry and space, or between the design and the building. This type of relationship between the two 'worlds' caused the spatial to emerge from the flat surface. Captured through geometry, the properties of space in architectural theory have since remained an *active* but silent partner.

3. VARIABLY STANDARD: GEOMETRIC CONTROL VS. VARIABLE SPATIAL FORM

Palladio's ideas travelled to the West in the 17th century, giving rise to English and American Palladianism. In the 19th century studies of classical architecture using the generative potential of taxonomy and classification were produced by Jean-Nicolas-Louis Durand (1760-1834) in his *Cours' d' Architecture*, a highly rationalised encyclopedic survey, consisting of formal schemata that are literally empty of any specific content (1805). The approach was rejected by the avant-garde architects in the 20th century, following ideas of organic evolutionary typology, based on studies such as those by D'Arcy Thomson (1860-1948). Yet, as Frampton has recently argued, there were three conflicting paradigms that shaped modernism: the technological, the classical, and the vernacular (or the organic) (2016). The first paradigm was about the impulse to use the technological methods of the period. The second one was a normative standard embodying a rational and international design culture. The vernacular model derived its strength from organically grown built examples and from regional building culture.

The first 'modern' architect before the modern movement was England's John Soane (1753-1857). In Lincoln's Inn Fields, Soane built incrementally a house that challenged the isometric invariance between design and building. The distribution of visual integration captures the grid-like geometry of Durand's system, but the axes of symmetry are broken and the enfilade sequence of rooms, usually arranged in perspectival recession in Classicism, is distorted. The axes of movement correspond neither with geometry nor with the axes of sight (Psarra 2009). Compared to the villa Rotonda, visual fields here not only have more variation in terms of shape, but also greater degrees of transformation along with movement (figure 2).It was Le Corbusier who intensively engaged more than any other architect with the organic, modern and classical models. In 1964 he published a site plan of his design of the Venice Hospital in his *Oeuvre*, showing the hospital behind the train station together with a selection of other buildings in Venice (figure 3). The drawing links the project with Palladio's San Giorgio Maggiore, via the Grand Canal dotted by Pallazzi, the Rialto, the Merceria and the Piazza San Marco. Le Corbusier had always aspired to design a public building in Venice comparable in scale and impact to that of Palladio's convent, the grand piazza and the Ospedale Civile. In his *Four Books*, Palladio described the convent as intended for the recreation of the 'houses of the ancients' (ibid.). Thus, the march from the service yard to the embellished front of the city and to San Giorgio

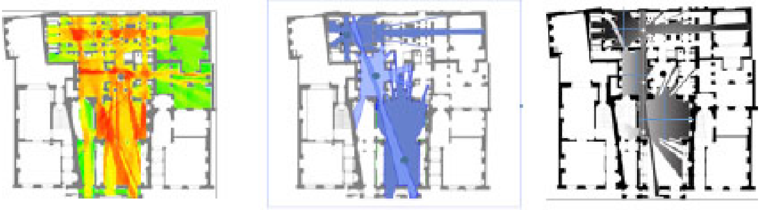

Figure 2 - Soane's Museum; Visual Integration (left); Isovist from points along axial line; Isovists and geometry of room enclosures

Maggiore in this map expresses Le Corbusier's heroic entrance to the legacy of architecture since Roman times. However, the link with Palladio's convent and church is not simply because Le Corbusier measured himself against the classical architect. It is also because he was aware of the disciplinary roots of architecture with its emphasis on mathematical literacy and geometry. It is in Venice that the first translation of Vitruvius was published, and it is in Venice and the Veneto where Palladio had practiced. Le Corbusier positions the hospital not only in the urban context, but also within the disciplinary tradition of structured architectural knowledge, rooted on classical humanism and against the organic context of Venice.

Figure 3 - Le Corbusier Site Plan of Venice

same time, he had absorbed other influences for the project: first, ideas of organic growth and evolutionary design that were prevalent in the 60s. Second, the urban structure of Venice based on interconnected squares, the separation and intersection of the two networks of movement, that is, canals and pedestrian pathways (Psarra 2011, 2013.) Third, the pin-wheel pattern, a schema that preoccupied him throughout his career. This pattern goes back to the *Villa La Roche* (1925) built for a wealthy client to house his painting collection. This is the house in which Le Corbusier invented the architectural promenade, guiding the visitor through changes of direction along ramps, stairs and raised pathways. In contrast to the axial structuring of movement through similar rooms in classical architecture, he used a twisting course of movement, covering heterogeneous elements. As opposed to geometry shaping human movement, he employed human empirical movement to shape the building.

But it was at the time he was designing the Villa Savoie (1928-1931) that the combination of a simple Platonic volume with a turning path shows up as the first instance of a career long paradigm of designing (figure 4).. At that time he was collaborating with Paul Otlet (1868-1944) on the Mundeneum (1929). Otlet was a significant figure in the history of information society and the networked knowledge base of the future The Mundeneum was intended as a place that would provide access to the world's knowledge. Otlet envisioned a 'city of knowledge' that would serve as a central repository for the world's information. The World City was a utopian vision, which like a universal exhibition would bring together all the leading institutions of the world. It was formed as a giant circulation ramp into a ziggurat-shape to test the spiral idea at a monumental scale. The two schemes, one domestic (Savoie), the other public (Mundeneum) were worked in parallel, combining the simple volumetric form with the pattern of twisting movement.

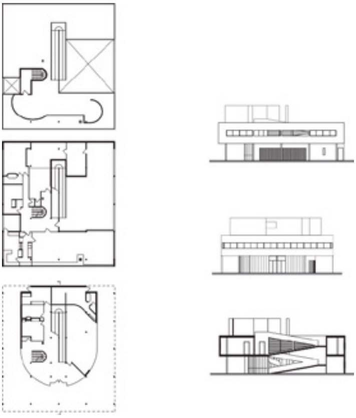

Figure 4 - Le Corbusier, Villa Savoie.

In the design for the Museum of Contemporary Art (1931) Le Corbusier shaped the whole building as a continuously unfolding wall. The museum is entered through an underground passage and is without façade, absorbing the exterior into the interior. A few cuts are made in its surface to allow the visitor to step outside the fixed itinerary and circulate in different ways. In 1936 he used the pinwheel pattern again in the Centre for Contemporary Aesthetics. In 1939 he used the same design theme in his designs for the French Pavilion in San Francisco and the exposition in Liege. The same year marks the Museum of Unlimited Growth in Algeria, in which the future expansion of the museum is based on a spiralling pattern indicated on the ground around the simple box-like form of the building. The rotating path is combined with a central void and four spaces, each on a different side of the volume, defining the pinwheel schema of composition. Le Corbusier used this schema in 23 designs of different scale and social programme, from museums and exhibition spaces to villas, including the monastery of La Tourette (figure 5)[2]. Why was he preoccupied with this schema so consistently and what impact does it make.

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[2] It turns out that with the exception of the period of the Second World-War, there is no more than a 3-year gap to the start of a new project that involves the spiral-swastika pattern. Total of 23 projects between 1923 and 1965. 1. Villa La Roch-Jeanneret 1923 2. Villa Meyer 1925; 3. Mundaneum 1928; 4. Museum of Contemporary Art 1931; 5. Bata Boutique, 1935;

6. University Campus Rio de Janeiro 1936; 7. Centre of Contemporary Aesthetics 1936; 8. Pavilion des Temps Nouveaux, 1937 9. Museum of Unlimited Growth , 1939; 10.French Pavilion in San Francisco, 1939; 11.Exposition Habitat 45, 1945; 12.Urban Development, Saint-Die, 1946; 13.Exposition Synthese Des Arts, Porte Maillot, 1949; 14.Cultural Centre of Ahmedabad, 1951; 15.Tokyo Museum, 1959; 16.Etude d'urbanisation, Meaux, 1957; 17.Le Couvent de la Tourette, 1950; 18.Museum at Chandigard, 1959; 19.Cultural Centre Chad , 1960; 20.Museum of the Twentieth Century, Eisenbach, 1963; 21.Museum of the Twentieth Century, Nantere, 1965; 22.Musee de lotissement undated; 23.Venice Hospital, Venice, 1965

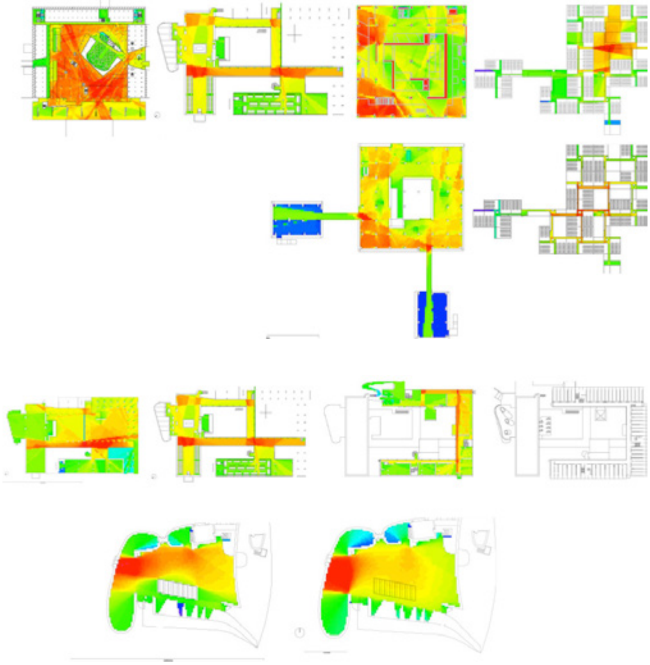

Figure 5 - Le Corbusier's Assembly at Chandigarh (top row left); La Tourette, (first row second left), Tokyo Museum (top row second right); Venice Hospital visibility integration (top row right); Cultural Centre at Ahmedabad, permeability Integration (second row left); Venice Hospital, permeability integration (second row right); La Tourette, ground floor (third row left); La Tourette, first floor (third row second left); La Tourette second floor (third row second right); Chapel at Ronchamp with furniture (bottom row left); Chapel at Ronchamp without furniture (bottom row right).

We can explore answers to this question in three projects, the only ones which were constructed based on the pinwheel scheme: the Tokyo Museum (1959), the Museum of the Cultural Centre at Ahmedabad (1951) and the Chandigard Museum (1959). As with the Rotonda, in the Tokyo Museum there are four such axial connections, linking the central space with the exterior (figure 6).Contrary to the Rotonda, these axial elements travel along the perimeter of the central hall rather than traversing the hall, which is placed at the geometrical centre. In addition, seeing the central hall is different from accessing this space, since there is a break in the classical link between visibility and movement. We see here the clear impact of inserting an object at the centre of a layout and pushing the values of integration to the corners of the space (Hillier 2003). Looking at the graph of the main spaces, we see that there is graph symmetry only with respect to space 1 – at the end of the ramp – which is off the main axis. In the classical model of composition there are usually more spaces that have graph symmetry in relation to other spaces, while at the same time the space with the highest value of integration is at the geometrical axis of the building (figure 1). Compared with the Rotonda, where there is isometric correspondence between geometry and space, the Tokyo Museum is a clear case of invariance between the two kinds of properties.

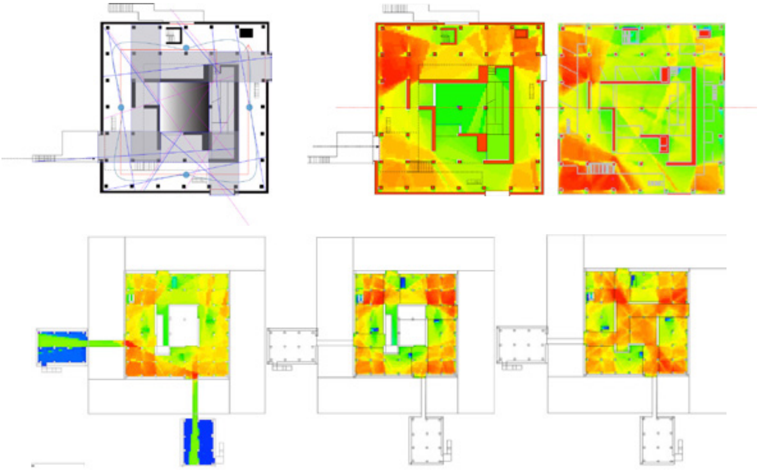

Figure 6 - Tokyo Museum. Axial lines of visibility and permeability (top left); Permeability visual integration (top middle); Visibility visual integration (top right); Cultural Centre at Ahmedabad; Permeability visual integration with pavilions (bottom left); Visibility visual integration (bottom middle); Permeability visual integration (bottom right)

Developed over thirty years of architectural activity the pinwheel pattern became for the Swiss architect a standard independent form, producing different variations on a theme, based on the invariance between geometry and the topological graph of a building[3]. There are three main mechanisms through which invariance between these two systems is generated: first, two-fold or four-fold symmetry in relation to the outer envelope and the central space; secondly, rotational symmetry articulating the relationship between the central space and the adjoining galleries, pathways or openings (the pinwheel plan); thirdly, placing a void at the centre and screening it from the rest of the layout, so as to disassociate the structure of views from the structure of movement.

Le Corbusier dismissed the Beaux-Arts approach to composition, which is appreciated on axis as anachronistic and dogmatic. Yet, he had a clear understanding of the strategies by which the close association of moving and viewing was achieved in classical buildings. He used long axes to organise a plan but in a way, which created variable rules, in the sense that what is invariant in one system is not the same with that which is invariant in the other. The spectator produced by this architecture shifts course with movement while exploring vistas that develop along different directions, but is always in reference to the classical logic of geometrical composition.

Freeing the various systems of properties from each other, or breaking the isometric invariance between geometry and space was a strategy that was widely adopted by modern architects. Many buildings seen in figure 7 use geometry simply as a supporting armature, rather than as a generator of the design. Invariance across systems is nonetheless, present in buildings by 'classical modernists', such as Terragni' Casa del Fascio, Mies' Crown Hall, Tugedthat House and Farnsworth House; Aldo van Eyck's church and Asplund's library in Stockholm. The nordic classicism of Asplund's library (figure 8) is particularly interesting when seen in relation to Palladio's Rotonda (figure 1) and Le Corbusier's Assembly in Chandigarh (figure 8), where a similar U-shaped geometry surrounds a main space with a circular chamber. However, although

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[3] The scheme of rotational symmetry through the swastika plan finds realisation even in his religious architecture, if for example we look at La Tourette and the three entrances in Ronchamp.

the three projects have a similar *parti*, their spatial systems are entirely different from each other.

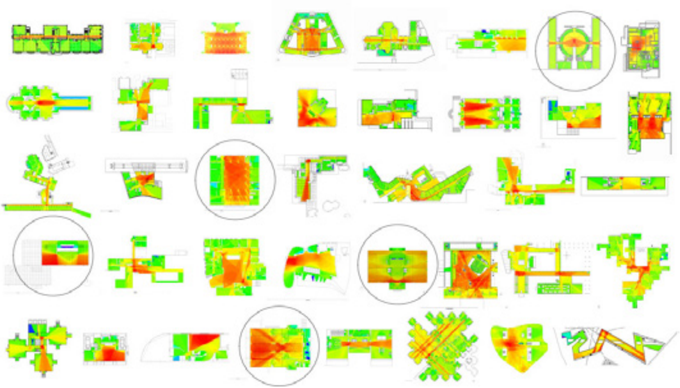

Figure 7 - Visual integration in a collection of 20th century modern buildings; Asplund Library, Stockholm, (top right - in circle); Terragni Casa di Fascio (third row - in circle); Mies van der Rohe Farnsworth House (fourth row left - in circle); Mies van der Rohe Crown Hall (fourth row middle – in circle); Aldo van Eyck's Church (bottom row – in circle)

As with Palladio who influenced modern architecture, the use of geometry and space by these early modern architects affected contemporary architectural practice. A key reference is Mario Botta's domestic architecture, using isometric invariance between geometry and space within the principles of tripartite composition, front and back distinction and the confines of the Platonic solid. Another reference is Rem Koolhaas' Kunsthal as a square volume perforated by two intersections, a road and a pedestrian ramp, and a continuous spiralling circuit of interior space that covers different spaces and programmes[4]. Another clear case is Herzog and De Meuron's De Young Museum in San Francisco (figure 9). The architects have used the corporeal geometry to inform the incorporeal geometries of moving and viewing. The building seems to gather all the elements of a Beaux-Arts Museum: an open courtyard, a tower, a grand staircase, a portico - and reassemble them in a new fashion. The reference of the building to the Baux-Arts is made evident by the analysis. In a manner that is reminiscent of Durand's axial grid-like composition, the pattern of integration picks up the axial lines of the building geometry, but replaces orthogonal geometry with an oblique system of geometrical planning. Contemporary architecture therefore, is still choreographed by the lines of sight and movement of the body.

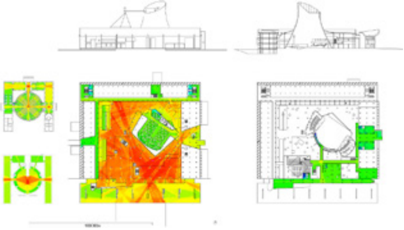

Figure 8 - Asplund's Library and Corbusier's Palace of the Assembly

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[4] The Kunsthal does not rely on isometric invariance between geometric and topological properties, but uses the idea of the promenade inside an orthogonal geometry.

4. NON STANDARD VARIATION

Traditional drawing was an additive process. The consistency and the essential associative relations between plan, section and elevation, between one element and another, between geometry and space were managed by the designer during the process of design. Raphael's method of orthographic projection guaranteed exactly that. Geometry was the practical, conceptual and intellectual network of associations needed to establish internal coherence. CAD software simply translated this additive logic within the digital realm. This means that even though geometry and space in modern architecture were decoupled, there were by and large no changes in terms of notational tools (plans, elevations and sections) or the strict repertory of orthogonal geometrical forms until the rise of digital technology.

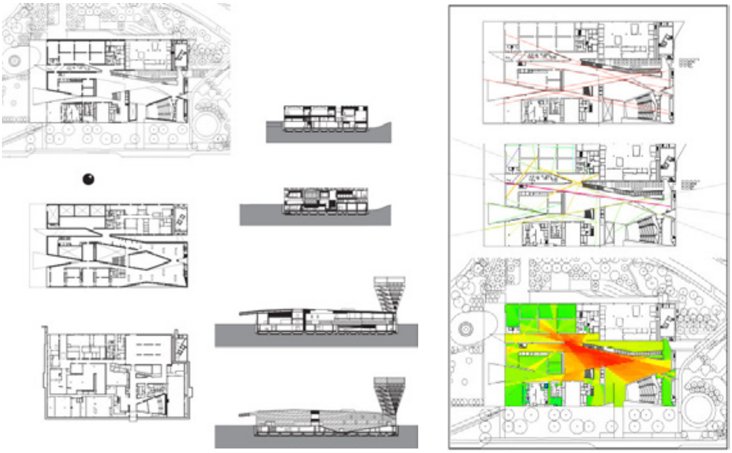

Figure 9 - Herjog and de' Meuron, De Young Museum.

Over the last decades, digital architecture has led to interactive algorithmic models based on associative logic, responding to variations in the design input by manipulating the entire system. *'They have already made it possible to envisage a continuous design and production process where one or more designers can intervene, on a variety of two-dimensional visualisations and three-dimensional representations (pint-outs) of the same object, and where all interventions or revisions can be incorporated into the same master file of the project'* (Carpo, ibid.). For Carpo, *'under the former dominion of geometry what was not measurable was not buildable. Now all that is digitally designed is, by definition and from the start, measured, hence geometrically defined and buildable... today's designers are not working on notations of objects but on interactive avatars of the objects themselves'* (ibid.). Further Deleuze and Cache's description of the 'objectile' defines design as an algorithm rather than as an object, a parametric function which may determine an infinite variety of objects, all different yet all similar as the underlying function is similar to all. Similar to Hillier and Hanson's notion of the genotype in the beady ring settlements, producing endless phenotypical variations of the same model, the objectile can be collaboratively manipulated by designers resulting in a series of non-identical elements. Carpo explains that together with the demise of geometrical notation there is no longer the Albertian author of identical mechanical copies (ibid.).

The invention of the digital not only enabled design to operate directly on three-dimensional coordinates, but also provided a vast repertory of forms freed from constraints imposed by buildable geometry. Yet, although orthogonal geometry, notations and the limitations they

impose on formal variability have gone, geometry and its essential link with space are not gone. Even when a building is not aesthetically revealed by spatial exploration, it still embodies relationships of geometry and movement. Design software can produce different formal outputs through inputs that affect the geometry of objects, but the impact of geometry on space outputs is still in the blind spot, still in the shadows of these data, components and node diagrams. It is here where the theory and method of space syntax can contribute, linking geometry and space, generative and analytical approaches to design. Prior to discussing the input of space syntax, it is important to explore what the appropriations of space and geometry discussed here mean for architecture.

5. TOPO-GEOMETRIC PROPERTIES

Tracing morphological paradigms, I explored how geometry influenced the development of architecture as liberal art concerned with conscious design. By foregrounding a geometric world of conceptual intelligibles, geometry in Classicism established an identity relationship between design and building, geometrisising spatial structure (which in the three-dimensional world is understood through moving and viewing) as a stable image. By externalising spatial relationships, it made spatial and symbolic messages more pronounced. The technological invention of the structural grid in the twentieth century lifted geometric constraints imposed by load bearing partitions. Freed from geometric limitations, modern architecture established variability in the relationship between geometry and movement.

Yet, in spite of different approaches, the complex relationship between geometry and space facilitated translations from one programme to the other, including from cities to architecture in both periods. Le Corbusier used the pinwheel scheme in public and private commissions, in different sites, programmes and cultural contexts. Many of his museums were incubated in his domestic architecture through the most private commissions. In *Un Maison - Un Palais* (1928), in which he expressed the extension of his ideas from the private house to public buildings and urban spaces, the villas became prototypes for a universal way of living, and the museum a prototype for the city[5]. Influenced by Alberti, Palladio also believed that a building is like a city. His villas and churches were based on his studies of Roman baths, which he interpreted as indoor miniaturized cities, theatrically framing space from the scale of the apse to the house and the landscape. Is it the trans-nationality of these projects, the expansion from the house to the scale of the museum, the hospital and the city as a whole, the intersection of social programmes that are functionally very dissimilar peculiar to Palladio, Le Corbusier and Mies or to the other contemporary architects?

For Beatrice Colomina domesticity has been the real source of modernity in Le Corbusier and Mies' museums (2009). I argue that the roots of modernity reach back into the villas of Palladio in which the pattern of interconnected rooms and their flexible use diffuse the boundaries between the house as a space for private living and the house as art gallery, performance space or theatre. In effect, Le Corbusier's application of the pinwheel plan across different building types and the translation of Venice's spatial structure in the Hospital reveal that these architects invested on generic properties of geometry and space over and above the functional programmes of house, museum, hospital or urban space.

In a building that is like a house, a museum and a city, functional demands imposed by site and social programme are just one filter among others. Without circumventing functional requirements, these architects were concerned with crafting geometry, space and exploring their limits in different frameworks of functionality. The relationship between these programmes and between the building and the city were based on topo-geometric properties that are common to all. By interfacing generic relationships related to urban space and architectural space, these architects extended over and above ontological and functional distinctions between functional building types, architecture and urban contexts. Topo-geometric properties of moving and viewing are shared among cities as multi-authored products of society and architecture as self-conscious product of design. If the former arise as the collective outcome of micro-economic activity and the reproducibility of culture, the latter are the result of conscious intentionality that recognises patterns common to all and translates them through creative invention.

[5] Palladio A. (2002), The Four Books of Architecture, Cambridge Mass: The MIT Press.

Describing space as a topological relational field, Hillier's analytic theory has in the last four decades studied buildings and cities in relation to human activity and function. Hillier explains that geometry gets into the topology of the urban network, affecting through the intersections of street lines and the angles of their incidence their spatial structure (1997). However, in spite of extensive application in real projects, the theory of configuration treats architecture and cities solely as empirical objects, based on properties of embodied movement and vision from the ground. It does not take into account how architecture is conceived and produced, including the ways in which generic properties of space and form get into the topology of buildings and streets traversing these two worlds from within and without. If space has been a silent partner in architectural discourse, geometry has been a silent conductor in the theory of spatial configuration. For Hillier, the reason for this deficit is that the relationship between design and use passes not through geometry or form but the realm of space (1996). Yet, with a clear focus on how cities and designs influence one another as revealed by this analysis, the picture is more complex than the clear-cut split into analysis and design, architecture and cities, aesthetic and social practice. The study of topo-geometric properties should make it possible to explore buildings and cities both as the non-authored products of society and the authored products of design.

The examples studied here help reveal a genealogy of ideas around which the concerns of architects converge and the architecture as a discipline is defined. Architecture concerns critical commitment to comparative architectural knowledge on the part of an empirical historical architect, that is, a person endowed with historical consciousness (and an unconscious). Historical consciousness means that the fact that Palladio built before Le Corbusier, and Le Corbusier operated before Rem Koolhaas is as significant as the morphological exploration of their buildings. Comparative knowledge and historical consciousness establish an architect's place in history in relation to the available knowledge of ideas and tools that shape the discipline up to one's present, together with the possibilities and limitations for the future one's historical position enables and withholds.

If innovation and the creative imagination proceed from the intersection of possibility with constraint, the intersection of comparative knowledge and dependence on historical sequence brings us to the question of the imagination. At the beginning of this paper I argued that digital technology might reduce architecture into a practice without a theory. If over the centuries Eucleidian geometry was a platform of mediation through which space/building could be visualised and ideas would be linked to the three-dimensional material world, in computational design mediation between the thought process and the empirical object is abstracted through algorithms and scripting. In the former the cognitive processes that underline design establishing consistency relationships between parts are with the designer. In the latter, the designer produces an interactive digital model responding to variations in the input by manipulating the entire system, enabling to design a process rather than a single object. Lending ideas syncretically to the eye all at once, geometry enabled architects to link form to space, idea to building and intuition to logic.

Computational design can provide the scientific and philosophical exploration of design possibility and virtuality, extending and surpassing the designer's intellect. However, it needs to engage the relationship between geometry and topology rather than simply the mathematically generated styles of software engagement. It also needs to bring the abstract logic of computational design into the realm of principled understanding and the historical sequence of ideas that influence architecture and the imagination. The architectural imagination transgresses functional constraints, social programmes, ontological and historical categories by transferring generic properties across different domains, in ways, which enable one to make innovations and overcome constraints in a work. The principles of space and geometry are not just generic tools, but also the instruments of the critical faculties in architect's imagination. Abstract comparative knowledge and historical consciousness can raise space and geometry from silent instruments to the level of abstract comparative thought, towards a unitary theory of generation and explanation in architecture and the architectural imagination – towards an archaeology of the present.

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#173

NORMALISATION OF MEASURES IN SEGMENT ANALYSIS USING BIOLOGICAL METHODS

ERMAL SHPUZA
Kennesaw State University
ermal@morphostudio.net

ABSTRACT

In biology, allometric scaling is used to calculate the body condition by comparing measurements of individual organisms to a population average, or baseline, as defined by the allometric equation. A growing number of studies has shown that scaling laws, one of the fundamental features of complex systems, govern many characteristics of urban form. Based on the scaling analogy between organisms and cities, this paper translates the body condition method from biology to urban studies to propose new normalised measures of segment analysis: allometric length, allometric connectivity, allometric angular depth and allometric least angle choice. The study is supported by the segment analysis of street networks in 70 Adriatic and Ionian coastal cities considered in three historical stages. Baselines for the proposed relativized measures are derived from the strong and significant allometry of segment measures. The proposed measures of allometric angular depth and allometric least angle choice are compared against NAIN and NACH (Hillier et al, 2012) resulting in various degrees of compatibility. The proposed allometric normalisation depends on the comparison of a city to a large sample of cities, and thus faces the challenge of dealing with cases that are not part of a regional or typological sample already studied. Based on the results of a previous comparison involving axial maps of a few samples of cities, we speculate that for cities with unknown allometry, adopting the normalisation formulae proposed here would produce more accurate indices than the existing measures by Hillier et al. The proposed method can be used to normalise any segment analysis measure that displays allometry in others scales of the built environment.

KEYWORDS

Normalisation, segment analysis, scaling, allometric subtraction, street network

1. INTRODUCTION

The rendering of size-invariant measures, also known as relativisation or normalisation, is a fundamental precondition for comparative studies that involve built complexes of different size. Segment analysis in space syntax opened the way for enriching the precursor axial map analysis with descriptions of human perception of built space related to angular changes in movement. Normalisation methods for segment analysis introduced a few years ago (Hillier et al, 2012) enabled important characterizations of streets linked to socio-economic aspects of cities including foreground and background networks, and dispersion of centrality. The method was developed upon a conceptual framework centered upon the human conception of distance as affected by change of direction, or angular deviation from the straight line. This led to a mathematical model that modified the least angle segment choice by taking into account angular depth between segments. This paper argues that the normalisation of angular depth and least angle choice in segment analysis by Hillier and his colleagues is problematic in two levels: first, it is based on empirical models that are validated based on correlations with observed patterns of pedestrian and vehicular movement; second, it approaches the normalisation of least angle segment choice by combining choice and depth, rather than relying on choice as

an independent variable on its own right. We propose new normalised measures for segment analysis that are based on the allometric scaling of segment measures by translating methods that were originally developed in life sciences in the 1970s. The study is supported by the analysis of a sample of 70 cities considered in three historical stages and analyzed with segment maps. The argument is developed in four main parts: first, we discuss the existing normalisation methods for segment analysis; second, we review allometric scaling and calculation of body condition in life sciences; third we propose normalised measures for segment analysis based on allometry; and finally, we compare the new measures to the existing ones.

2. NORMALISATION OF DEPTH AND CHOICE IN SEGMENT ANALYSIS

The normalisation of segment angular depth NAIN is built upon an empirical model that is aimed at capturing the manner in which angular depth is structured in real city examples and is validated based on high correlations with observed patterns of pedestrian and vehicular movement. Methods that use fixed yardsticks for normalisation are problematic since they rely on observations that might be quite different from other samples to be analyzed in the future. The measure of choice was part of the early space syntax toolbox (Hillier et al., 1987). Although it is based on its own original conceptualization of a spatial network as a justified graph, it produces the same results as the measure of betweenness centrality, which quantifies the number of times a node is used as a bridge in the shortest-path travels from each node to all others in the network (Freeman, 1977). The approach for the normalisation of least angle choice (Hillier et al, 2012) considers the measures of choice and depth as coupled. This is based on the need to improve the power of spatial analysis as a predictor of pedestrian and vehicular movement in the city. Therefore, the normalisation of least angle choice was framed as a problem solving of the so-called choice paradox, where the amount of choice for a segment is related to the integration of the segment, while the total choice of the network is related to its segregation. The mathematical model for normalising choice is then developed in a cost-benefit way related to the human perception of angular depth, i.e. amount of deviation from the linear during travel in a spatial complex. We argue that such approach raises two additional issues: First, the normalisation of choice is dependent on the measure of depth; hence, the current normalisation of choice is indeed a normalisation of the combined choice-depth product. Second, similar to the earlier discussion on depth, such normalisation has been validated based on the strength of predicting levels of movement, and is therefore dependent upon another external measure. Is it possible to normalise choice as an independent variable without relying on angular depth or levels of pedestrian and vehicular movement? The paper tackles this question by translating normalisation methods originally developed in biology.

3. ALLOMETRIC SCALING AND BODY CONDITION IN LIFE SCIENCES

Allometry describes the effect of size on the proportion of measures in an organism during growth (Huxley, 1932; Kleiber, 1932; von Bertalanffy, 1951). Allometry is expressed according to two equivalent equations

$$Y = Y_0 N^{\beta} \qquad \text{or} \qquad lnY = lnY_0 + \beta lnN \qquad (1)$$

where β is the scaling exponent or allometric slope, and Y_0 a constant. Two variables have an allometric relationship when they display a strong linear correlation in a log-log plot.

The calculation of body condition is one of the main applications of allometric scaling in life sciences. Body condition, or condition index, results as the concept of animal's health state by removing the size effect from the weight-length coefficient, or ponderal index (Rohrer, 1921; Thompson, 1961). Body condition is usually estimated according to the residual index method by comparing residual distances of observed points from the predicted points that lie on the line of least-square linear regression of body mass against body length, where the data are usually log-transformed (Gould, 1975; Harvey and Pagel, 1991)

$$ln\hat{\varepsilon} = lnY - lnY' \qquad \text{or} \qquad \hat{\varepsilon} = \exp(lnY - lnY') \qquad (2)$$

where Y is the actual value, Y' is the predicted value, and $\hat{\varepsilon}$ is the residual.

4. ALLOMETRY IN SEGMENT ANALYSIS MEASURES

Allometry and scaling in general have expanded from biology to many other branches of sciences including urban studies, where first discoveries included the scalar relationship between urban population and city size (Naroll and von Bertalanffy, 1956; Stewart, 1947). Ranko Bon pioneered the allometric study of formal aspects of the built environment with findings on the scaling of metric length in circulation networks in buildings and road networks in islands (Bon, 1973; Bon, 1979; Steadman, 2006), during his work with the Philomorphs, an interdisciplinary seminar directed by Arthur Loeb at the Harvard in the '70s. Recent interdisciplinary research in urban studies, geography, and network theory has shown that just like organisms and ecosystems cities conform to scaling laws since they are based on emergent bottom-up processes of social and spatial networks, (Barthélemy 2013; Batty, 2008; Bettencourt and West, 2010; Makse et al., 1995). Allometric scaling is shown to apply to topological measures of street networks (Jiang, 2007; Jiang and Claramunt, 2004) and metric and syntactic measures of axial maps (Shpuza, 2014; Shpuza, 2017). This study is based on the allometric analysis of segment maps of a sample of 70 coastal cities in the Adriatic and Ionian littoral region (hereafter referred to as AI) considered in three historical stages from 19th century, WW2 and 2002-2010 (referred to as S1, S2 and S3) (figure 1), previously analyzed with axial maps. The cities include a wide variety of street patterns, which reflect various socio-political and physiographic influences (Shpuza, 2007). Street networks are defined according to the contiguity of built form and disregarding administrative boundaries (Shpuza, 2011). Segment maps are generated from manually drawn axial maps and analyzed with UCL Depthmap software (Turner, 2010; Varoudis, 2016) by removing stubs of up to 40% in length.

Four allometric relationships are examined from the log-log plots for the segment measures of AI sample: 1) overall length L (not shown in table) to network size N; 2) overall connectivity C to N; 3) overall angular depth D to N; and 4) overall least angle choice B to N (table 1). Overall values are calculated as products of mean values and network size.

The scaling exponents β (1.152, 0.993, 2.271, 2.573) for allometric relationships of length, connectivity, angular depth and least angle choice for AI segment map analysis (table 2) differ slightly to length, connectivity, depth and choice (1.086, 0.968, 2.360 and 2.408) reported for the same sample analyzed with axial maps (Shpuza, 2017). Compared to axial analysis, super-linear scaling of segment length and least angle choice is further increased; super-linear scaling of angular depth decreases; whereas segment connectivity becomes practically linear.

Figure 1 - Map of 70 selected towns and cities along the Adriatic and Ionian coastline

	City	N			$\bar{C}$			$\bar{D}$			$\bar{B}$		
	Country	1	2	1	2	1	2	1	2	3	1	2	3
	GREECE												
1	Koroni	400	503	670	3.9	4.0	3.9	1953	1808	3117	4655	4960	8752
2	Methoni	385	482	707	4.0	3.8	3.7	1933	1887	3052	4646	5086	8252
3	Pylos	254	546	823	3.8	3.9	3.9	905	2127	3629	2716	5977	13687
4	Zakynthos	1000	998	1535	4.0	4.0	4.0	4223	4220	6601	20245	20283	38498
5	Patras	1009	2931	14696	4.6	4.4	4.0	2846	11953	116083	12738	75340	1074060
6	Aigio	403	982	3950	3.9	4.2	3.8	1370	3285	23926	3451	14818	146363
7	Korinthos	166	613	2061	5.1	4.4	4.0	268	2020	9420	479	7387	48832
8	Nafpaktos	310	712	1892	3.7	3.9	3.8	1820	3676	9886	2983	10184	58634
9	Messolonghi	559	852	2240	4.1	4.3	4.2	1684	2428	8092	6002	12735	56069
10	Lefkada	760	906	1714	4.1	4.2	4.1	2519	2894	6421	11871	16097	39163
11	Vonitsa	393	554	1133	3.8	3.9	4.0	1497	2038	4114	4842	7229	18868
12	Preveza	493	890	2264	3.8	3.9	3.9	1957	4071	10927	6189	14376	59112
13	Kerkyra	1506	2229	6522	3.9	3.9	3.5	7174	11932	51943	27972	54529	401697
	ALBANIA												
14	Sarandë	132	257	4624	3.8	3.7	3.5	306	659	50591	665	2645	238747
15	Vlorë	432	1213	10938	3.7	3.7	3.5	1553	5147	94235	4771	24836	735455
16	Durrës	296	1484	12958	3.6	3.7	3.5	932	6488	97596	2582	30735	1093680
	MONTENEGRO												
17	Budva	186	243	2352	3.8	3.8	3.6	522	730	13484	1154	1684	65647
18	Kotor	275	354	1349	3.7	3.6	3.3	1146	1795	10323	2165	3547	40692
19	Herceg Novi	203	579	2943	3.5	3.4	3.4	833	3159	27790	1566	9760	125087
	CROATIA												
20	Dubrovnik	948	2097	3217	3.7	3.5	3.5	4940	15237	23559	16755	67981	112435
21	Korčula	334	454	793	3.8	3.9	3.7	1508	1810	4923	4166	7038	17962
22	Hvar	444	656	1150	3.9	3.8	3.6	1945	3657	8170	3566	7984	21467
23	Stari Grad, Hvar	438	699	1139	3.8	3.7	3.7	1751	3542	7857	5570	9844	27495
24	Makarska	246	353	1779	3.9	3.9	3.6	679	1121	8157	1680	3034	47116
25	Omiš	103	176	1015	3.3	3.4	3.3	294	566	5828	550	1356	37626
26	Split	1552	2436	13097	3.7	3.9	3.6	9065	12187	104253	29607	56249	643955
27	Šibenik	758	1282	2871	3.8	3.8	3.7	3809	6293	19493	9682	21511	82935
28	Biograd na Moru	143	291	2029	3.5	3.7	3.8	546	943	9171	664	2294	58005
29	Zadar	540	1217	8581	4.0	3.8	3.5	1761	5928	69208	5812	25146	460275
30	Senj	375	525	1367	3.7	3.6	3.4	1430	2267	8910	3571	5964	27772
31	Rijeka-Kastav	501	4793	22466	4.2	3.7	3.4	1446	37188	379178	5154	233618	2266420
32	Opatija-Volosko	589	781	1780	3.3	3.4	3.2	3223	4315	15004	6886	9656	47431
33	Pula	263	1816	4333	3.9	4.2	3.7	699	7728	28371	1883	36023	127332
34	Rovinj	619	759	2255	3.7	3.7	3.6	3239	4335	17517	8541	9954	59428
35	Poreč	184	370	1751	3.8	4.0	3.6	432	1004	8864	1046	3790	36105
36	Umag	127	232	1574	4.2	3.9	3.7	233	625	7282	573	1806	33550

Table 1. (first part) - Catalogue of seventy towns and cities along the Adriatic and Ionian coast (listed counterclockwise from Peloponnese to Sicily) over three historical stages (1, 2 and 3). Segment analysis measures: number of segments N, mean connectivity $\bar{C}$, mean angular depth $\bar{D}$, and mean least angle choice $\bar{B}$.

	City	N			$\bar{C}$			$\bar{D}$			$\bar{B}$		
	Country	1	2	3	1	2	3	1	2	3	1	2	3
	SLOVENIA												
37	Piran	575	779	921	3.7	3.9	3.9	2279	3013	4083	8300	12129	17021
38	Izola	372	656	1869	3.8	4.0	3.7	1123	2274	9637	3882	8930	40219
39	Koper	937	999	4122	3.9	4.0	3.7	3589	3915	29128	15266	17040	137519
	ITALY												
40	Muggia	188	390	1241	3.6	3.6	3.3	557	1397	8427	1233	4327	31756
41	Trieste	1433	6826	14855	4.2	3.9	3.6	6413	50282	158701	28047	296451	915592
42	Monfalcone	231	1275	5141	3.7	3.8	3.7	669	5223	29806	1792	24420	249158
43	Grado	112	466	1057	3.7	4.5	4.2	316	1419	4406	396	4138	19332
44	Venezia	6866	7478	7455	3.5	3.7	3.6	147026	110949	110410	530036	449060	446634
45	Chioggia	552	1649	5890	3.8	4.0	3.7	1913	7170	35017	8184	46037	335068
46	Cesenatico	93	442	2259	3.9	4.2	3.9	217	1330	14596	254	4651	65867
47	Pesaro	586	1733	6961	4.0	4.0	3.8	1677	6629	49194	7089	33251	321145
48	Fano	443	1043	3876	4.0	4.2	3.8	1147	3046	20436	4514	18048	141281
49	Ancona	1014	2210	9361	3.7	3.8	3.6	5051	13070	80775	20941	52248	459770
50	San Benedetto	321	884	3009	4.4	4.4	4.0	935	2680	13472	2299	13409	97439
51	Ortona	321	667	1476	4.4	4.2	4.1	818	2186	6404	3054	8722	37420
52	Termoli	166	533	3437	3.8	4.0	3.5	475	2146	27770	1068	6796	117013
53	Manfredonia	183	401	3666	4.6	4.4	4.2	324	958	18339	751	3477	143111
54	Barletta	614	1101	3426	4.2	4.3	3.9	1933	3581	17402	8859	18401	126257
55	Trani	674	1414	5043	4.0	4.3	3.8	2419	4895	22833	8940	25680	252415
56	Molfetta	532	1276	3567	4.4	4.6	4.3	1625	4048	14506	5771	20771	114484
57	Bari	908	2360	7183	4.0	4.3	4.0	4193	10753	39447	13496	59359	323585
58	Monopoli	631	1047	3967	3.7	4.0	3.9	3064	5045	20946	9307	17051	130792
59	Brindisi	802	1973	5527	4.1	4.0	3.9	2933	11326	36372	10540	51621	219470
60	Otranto	194	351	1074	3.7	3.7	3.6	615	1367	7450	1177	2835	20938
61	Gallipoli	486	936	1867	3.7	4.1	4.0	1972	4703	10156	5597	17624	53672
62	Taranto	982	1997	5282	4.0	4.2	3.9	3353	11898	39839	23567	61361	245376
63	Crotone	804	1313	2237	4.1	4.3	4.1	3525	5679	10149	9497	20245	45261
64	Reggio Calabria	469	2355	7108	4.2	4.3	3.7	1432	10086	51850	4599	67313	351746
65	Messina	1978	4077	14571	4.5	4.3	3.6	6577	18804	146921	44075	143056	1027130
66	Acireale	1293	1673	4913	3.8	3.7	3.6	7045	9558	33912	26172	39479	204526
67	Catania	2273	5718	22114	4.2	4.2	3.7	8763	27433	223412	58353	240609	1797320
68	Augusta	225	448	1245	4.0	3.8	4.0	497	1368	5641	1671	5479	24593
69	Siracusa	787	1549	6339	3.7	4.2	3.8	3082	7231	47732	11781	36237	281634
70	Avola	779	1821	4152	4.0	4.4	4.3	2086	5945	15889	13528	40536	147028
	Min	93	176	670	3.3	3.4	3.2	217	566	3052	254	1356	8252
	Max	6866	7478	22466	5.1	4.6	4.3	147026	110949	379178	530036	449060	2266420
	Mean	659.3	1372.9	4611.1	3.9	4.0	3.8	4316	7750	37743	16020	38518	247431

Table 1 (second part)

Plot	Linear Fit Equation	R^2	Allometric Equation
$\ln L$ vs $\ln N$	y=1.152x+2.291	0.941	$L = 9.885N^{1.152}$
$\ln C$ vs $\ln N$	y=0.993x+1.403	0.996	$C = 4.067N^{0.993}$
$\ln D$ vs $\ln N$	y=2.271x-0.394	0.991	$D = 0.674N^{2.271}$
$\ln B$ vs $\ln N$	y=2.573x-1.127	0.997	$B = 0.324N^{2.573}$

Table 2 - Statistics of log-log plots and the resulting allometric equations of L, C, D and B versus magnitude N calculated for the sample of 70 Adriatic and Ionian coastal cities in three historical stages (210 cases) analyzed with segment maps. All logarithmic measures presented in the paper are in natural base, and all correlations have significance at $p<0.0001$.

5. NORMALISED MEASURES OF SEGMENT ANALYSIS BASED ON ALLOMETRIC SUBTRACTION

This study follows the long tradition of formulating descriptive models in architectural morphology by translating descriptive models from biology (March and Steadman, 1971; Steadman, 1979; Steadman, 1983; Steadman and Mitchell, 2010). The paper proposes normalised allometric measures Y_a^X for segment analysis by applying the allometric subtraction model recently developed for normalisation of measures in axial analysis (Shpuza, 2017).

$$Y_a^X = \exp(lnY - \ln Y') \qquad (3)$$

The subscript 'a' denotes allometry, while the superscript 'X' denotes the measure of size used for deriving the allometric relationship. The allometric measure is formulated analogously to body condition of an organism (eq. 2), by comparing the observed value Y for the city against the predicted value Y', i.e. the allometric average condition for the sample of cities. The latter is calculated from the allometric equation between Y and the size variable X.

We define four allometric measures based on the criterion of allometric subtraction in order to quantify in a scale-invariant manner segment analysis measures: lengt L_a^N, connectivity C_a^N, angular depth D_a^N, and least angle choice B_a^N (table 3). Values of allometric measures vary about 1 so that values smaller than 1 indicate a condition below the allometric average for the sample, while values greater than 1 indicate a condition above.

Allometric Formula	Min	Max	Mean
$L_a^N = \exp(InL - \ln(9.885N^{1.152}))$	0.481	3.972	1.058
$C_a^N = \exp(InC - \ln(4.067N^{0.993}))$	0.834	1.299	1.002
$D_a^N = \exp(InD - \ln(0.674N^{2.271}))$	0.594	2.899	1.034
$B_a^N = \exp(InB - \ln(0.674N^{2.271}))$	0.476	2.167	1.015

Table 3 - Measures of allometric length L_a^N, allometric connectivity C_a^N , allometric angular depth D_a^N and allometric least angle choice B_a^N derived from allometric equations (table 2) for segment maps of the sample of 70 Adriatic and Ionian coastal cities in three historical stages (210 cases). Values L, C, D and B are the totals for each city and are calculated with products between means and network size N.

The proposed normalised allometric measure characterizes the entire city. The allometric measure for a network component, e.g. a segment in the segment map, is calculated by proportioning the allometric measure for the city by the ratio between the measure for the component and the city aggregate. For example, the allometric angular depth for a segment d_a^N is calculated as

$$d_{a,i}^N = \frac{d_i}{D} D_a^N \quad \text{or} \quad d_{a,i}^N = \frac{d_i D_a^N}{N\bar{D}} \qquad (4)$$

where D_a^N is the allometric angular depth, D is the aggregate of angular depth d for each segment, d_i is the angular depth of a segment to all other segments, N is the number of segments in the map, and $\bar{D}$ is the mean angular depth. The other allometric measures for network components are calculated similarly.

The comparison between allometric measures and existing segment analysis measures (figure 2) shows mixed results. Strong correlations for length $\bar{L}$ versus L_a^N (R2 = 0.753), connectivity $\bar{C}$ versus C_a^N (R2 = 0.989), and integration $\overline{NAIN}$ versus allometric angular depth D_a^N (R2=0.783) shows that, while not precise, using the existing measures gives good approximations to allometric measures. The non-existent correlation (R2 = 0.074) between least angle choice $\overline{NACH}$ and allometric least angle B_a^N choice shows the two measures are incompatible. The allometric least angle choice is calculated based on the comparison to values of choice in a large sample of cities, instead of the existing normalised least angle choice NACH, which is a product of both depth and choice.

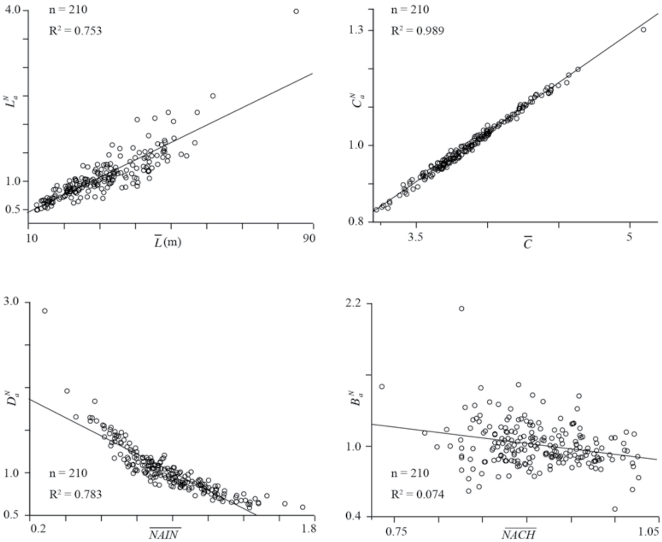

Figure 2 - Comparative plots between the existing measures and the proposed allometric measures for segment maps of 70 Adriatic and Ionian cities in three historical stages, 210 data points: a) mean metric length $\bar{L}$ versus allometric segment length L_a^N; b) mean connectivity $\bar{C}$ versus allometric segment connectivity C_a^N; c) mean normalised angular integration $\overline{NAIN}$ versus allometric angular depth D_a^N; d) mean normalised least angle choice $\overline{NACH}$ versus allometric least angle choice B_a^N.

6. ALLOMETRIC STAR MODELS FOR COMPARATIVE STUDIES

When the proposed allometric measures for segment analysis are employed for comparative urban studies, the four-pointed star model (Hillier et al., 2012) is modified such that D^N_a, B^N_a, minimum $d^N_{a,i}$ (as an inverse of integration) and maximum $b^N_{a,i}$ replace mean NAIN, mean NACH, maximum angular integration, and maximum least angle choice (figure 3). As a corollary of equation (4), the mean of $d^N_{a,i}$ for all segments in the map equals the allometric measure for the entire city D^N_a, whereas the mean of $b^N_{a,i}$ equals B^N_a. The proposed allometric measures are not only normalised, where the measures are rendered size free for inter-sample comparative studies, they are also calculated based on the allometric curve, which serves as a mean for the sample. Therefore, the vertical axis of the star model constructed with allometric measures does not require standardization with z-scores as in the original version (Hillier et al, 2012). The vertical axis in the four-pointed star is scaled from -1.50 at the center to 1.50 on top and bottom in order to accommodate D^N_a values, which range from 0.594 to 2.899, and B^N_a values, which range from 0.476 to 2.167 (table 3). The variation of D^N_a and B^N_a is a characteristic of the AI sample, thus the scaling of the vertical axis of the star model might differ for other city samples. The $mind(d^N_{a,i})$ values for the AI sample range from 2.632E-05 for Catania-2007 to 0.00783 for Biograd 1826, with a mean of 0.001086 and a standard deviation σ= 0.0013255. The $max(b^N_{a,i})$ values range from 0.000329 for Korinthos-2003 to 0.05697 for Omiš -1834, with a mean of 0.0135289 and σ =0.0095296. For the purpose of star model, the values of $mind(d^N_{a,i})$ and $max(b^N_{a,i})$ values in the horizontal axis are converted into z-scores

$$z = \frac{x - \mu}{\sigma} \qquad (5)$$

where x is the raw score of $mind(d^N_{a,i})$ or $max(b^N_{a,i})$ values, σ is the standard deviation, and μ is the mean. The star model is scaled with $mind(d^N_{a,i})$ z-scores, which range from -0.799 to 5.084 and $max(b^N_{a,i})$ z-scores, which range from -1.385 to 4.56. The $mind(d^N_{a,i})$ outliers include small towns Grado-1825, Cesenatico-1818, Omiš-1834, and Biograd 1826 with z-scores greater than 3. The $max(b^N_{a,i})$ outliers include also small towns of Cesenatico-1818, Umag-1873, Umag-1943, and Omiš-1834 with z-scores greater than 3.

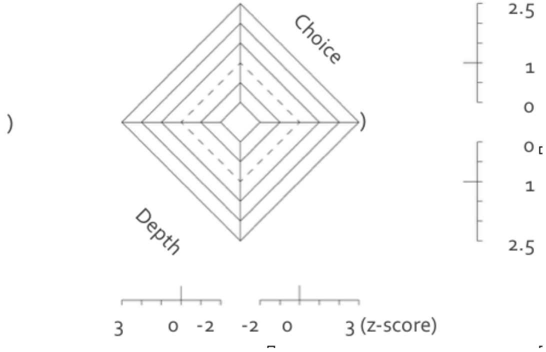

Figure 3 - Base four-pointed star model with normalised allometric measures for segment analysis: top) allometric least angle choice B^N_a; right) highest least angle choice value b^N_a; bottom) allometric angular depth D^N_a; left) lowest angular depth value d^N_a. The 1-0-1-0 value rhombus is shown dashed.

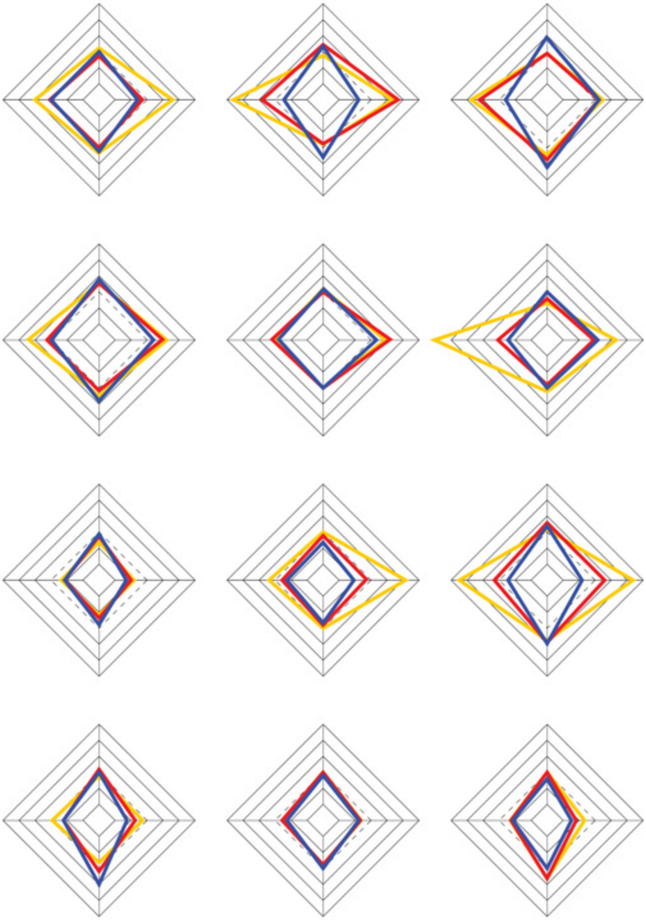

Figure 4 - Star models with normalised segment analysis measures B^{N}_{a}, $max(b^{N}_{a,i})$, D^{N}_{a} and $mind(d^{N}_{a,i})$ for 12 cities in three historical stages, S1 in orange, S2 in red and S3 in blue with smallest networks in upper two rows and largest networks in lower two rows.

We illustrate in star models 12 cities in three historical stages (figure 4), selected as the smallest segment maps in the third historical stage S3: Koroni, Greece 1829-1945-2003; Sarandë, Albania 1925-1945-2006; Kotor, Montenegro 1838-1943-2005; Korčula, Croatia 1836-1940-2003; Piran, Slovenia 1818-1943-2005; and Grado, Italy 1825-1943-2005, and the largest segment maps in S3 in the six countries on the Adriatic and Ionian coastline: Patras, Greece 1894-1943-2007; Durrës, Albania 1876-1943-2007; Herceg Novi, Montenegro 1838-1940-2007; Rijeka, Croatia 1865-1950-2007; Koper, Slovenia 1819-1956-2006; and Catania, Italy 1820-1942-2007. Considering the 36 selected cases (figure 4), small networks display a greater departure from the allometric mean, i.e. the 0-value rhombus in the center of the star model. This is observed both in terms of the comparison between smaller towns and larger cities, as well as between the smaller networks in the first historical period S1 (orange), and the larger networks in the subsequent periods S2 (red) and S3 (blue). The distribution of proposed allometric measures considered separately according to subsamples of 70 cases for three historical stages S1, S2 and S3 results in means around 1, while skewness values are much higher for allometric angular depth during S1 at 2.755 and allometric least angle choice during S3 at 2.308 (table 4).

	B^N_a	$max(b^N_{a,i})$	D^N_a	$mind(d^N_{a,i})$
S1	0.156	1.133	2.755	1.691
S2	0.888	1.370	1.231	1.619
S3	2.308	0.967	0.958	1.416

Table 4 - Skewness of distribution of B^N_a, $max(b^N_{a,i})$, D^N_a and $mind(d^N_{a,i})$ for subsamples of three historical periods S1 (1800-1900), S2 (WW2) and S3 (2002-2010) of the AI towns and cities.

7. CONCLUSIONS

The study proposes normalised measures for segment analysis based on the allometric subtraction, one of the most common methods in biology for quantifying the body condition of an organism. The study is supported by the analysis of a sample of 70 coastal cities in the Adriatic and Ionian region considered in three historical stages. The translation of biological methods for the study of cities is based on the functional analogy between cities and organisms as expressed by the existence of strong and significant allometric scaling of length, connectivity, angular depth and least angle choice in segment map analysis. Allometric measures show various degrees of compatibility with existing normalised segment measures, while there is a complete lack of correspondence between normalised choice NACH and allometric choice. Star models for comparative studies are modified with the new allometric measures; they reveal changes in depth and choice during urban growth. The allometric subtraction produces measures that are tied to a sample of study and therefore face the issue of applying allometric formulae for cities that belong to samples not yet analyzed. While this problem requires further analysis with additional city samples, a previous study of axial maps (Shpuza, 2017) has shown that applying allometric measures generated in other city samples produces more reliable results than using normalised measures that are based on means or theoretical yardsticks. The proposed method can be used to generate normalised measures for segment maps of any scale of the built environment.

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REPRESENTATIONS OF STREET NETWORKS IN SPACE SYNTAX:

Towards flexible maps and multiple graphs

GIANNA STAVROULAKI
Chalmers University of Technology, Department of Architecture
gianna.stavroulaki@chalmers.se

LARS MARCUS
Chalmers University of Technology, Department of Architecture
lars.marcus@chalmers.se

META BERGHAUSER PONT
Chalmers University of Technology, Department of Architecture
meta.berghauserpont@chalmers.se

LEONARD CARL STAFFAN NILSSON
Chalmers University of Technology, Department of Architecture
leonard.nilsson@chalmers.se

ABSTRACT

The shift from Axial to Line-segment maps is one of the most important developments in Space Syntax analysis, both theoretically and methodologically. It followed a long line of investigations and discussions within the field of Space Syntax, which addressed critical issues related to the Axial map representation (e.g. Hillier and Iida,2005; Hillier,1999a,1999b; Turner,2001; Steadman,2004, Dalton, 2001). At the same time, it opened up new possibilities by allowing for the use of Road-centre-line maps in Space Syntax analysis; that is, largely available GIS-based segment maps, used in most areas of urban modelling (e.g. Turner,2007; Dalton et al.,2003). Today, several models implement syntactical analysis to Road-centre-line maps, while claiming to form valid alternatives to the Axial map, not least in capturing the perceptual and cognitive affordances presented by the environment.

This paper focuses on such alternative models with a twofold aim: first, to help make well-grounded choices in applying syntactical analysis to Road-centre-line maps; and second, to explore the methodological potentials of Line-segment maps, which are created by their flexibility, by being the least aggregated representations of street networks. The paper introduces an experimental software application to push the investigations and exploit these methodological possibilities even further.

The models discussed in this paper are: 1) Angular Segment Analysis (e.g. Turner,2007; Hillier and Iida,2005); 2) Natural Streets maps (Jiang and Liu,2007) and Continuity maps (Figueiredo and Amorim,2005); 3) Directional Distance model (Peponis et al.,2008). Based on a systematic comparison of: a) their geometric representation of the street network (the 'map'), b) the dual-graph they calculate, and c) the measure of distance they use, we argue that they can all be seen as parametrically defined representations, based on a Line-segment map. In other words, with the same Line-segment map one could produce all of them, if a different set of angular parameters was used, to either define the graph elements (nodes, edges), or to calculate

distance. These models, parametrically redefine the relation between the 'map' and the 'graph'; thus, challenging the one-to-one relation between the two, that the Axial map was founded upon.

The methodological importance of this development goes beyond the specific models described in this paper. If the same Line-segment map can produce different graphs by using a different set of angular parameters, then, for instance, one could easily change the parameters to follow the latest theoretical insights on human cognition, without having to change the map. Going even further, one could develop and test different representational models to explore new theoretical and methodological paths, by using one single map. The experimental tool also presented in this paper is a step in that direction, allowing to test different models using a single software.

KEYWORDS

representation, graph, Axial map, Line-segment map, Road-centre-line map

1. INTRODUCTION

The Axial map has been Space Syntax's emblematic representation when it comes to urban modelling. Although it is not merely a representation of the street network, it has been largely used as such, with fruitful results in the study of urban space. The gradual shift from Axial to Line-segment maps is one of the most important developments in Space Syntax analysis both theoretically and methodologically. It followed a long line of investigations and discussions within the field of Space Syntax, which addressed critical issues related to the Axial map representation (e.g.Hillier and Iida,2005; Hillier,1999a,1999b; Hillier and Penn,2004;Turner,2001; Dalton,2001; Steadman,2004; Ratti,2004; Batty,2013). At the same time, it opened up new possibilities by allowing for the use of Road-centre-line maps in Space Syntax analysis; that is, largely available GIS-based segment maps, used in most areas of urban modelling (e.g.Turner,2007;Dalton et al.,2003). Today, several models implement syntactical analysis to Road-centre-line maps, while claiming to form valid alternatives to the Axial map, not least in capturing the perceptual and cognitive affordances presented by the environment.

This paper focuses on such alternative models with a twofold aim: first, to help make well-grounded choices in applying syntactical analysis to Road-centre-line maps; and second, to explore the greater methodological potentials of Line-segment maps, which are created by their flexibility, by being the least aggregated representations of street networks. The paper introduces an experimental software application to push the investigations and exploit these methodological possibilities even further.

The models discussed in this paper are: 1)Angular Segment Analysis (e.g.Turner,2007; Hillier and Iida,2005); 2)Natural Streets maps (Jiang and Liu,2007) and Continuity maps (Figueiredo and Amorim,2005); 3)Directional Distance model (Peponis et al.,2008). The model descriptions focus on three fundamental choices: a) the geometric representation of the street network (the 'map') b) the dual graph they produce and c) the measure of distance they use, in relation to their viewpoints on environmental perception and cognition.

The aim of this paper goes beyond the systematic comparison of different models. Figueiredo(2015) has already provided a similar and comprehensive overview, although with a different aim and perspective. Our model description is far from being exhaustive, as for example the models are not compared against empirical data, nor their ability to capture pedestrian and vehicular movement is tested and scrutinized. Our focus lies on the fundamental elements of the representation and analysis. Our purpose is to explore and build on a central idea proposed collectively by these models; an idea highlighted after close inspection and comparison. We argue that they all take the step to introduce angular parameters in the representation and analysis of street networks, although in different variations. We consider this methodological step of great importance as they parametrically redefine the relation between the 'map' and

the ‘graph’; thus, challenging the one-to-one relation between the two, that the Axial map was founded upon. Once they relativized this closed relationship by adding parameters, they opened up great methodological possibilities for future research.

One of the potentials, that we explore further in this paper, is that they can all be seen as parametrically defined representations, based on a Line-segment map. In other words, with the same Line-segment map one could produce all of them, if a different set of parameters was used; more interestingly, one could produce even more. To exploit this potential further, we developed an experimental software, allowing to create alternative models based on different parameters, using a single Line-segment map.

In the first chapter, we introduce the background of Space Syntax representations, focusing on the Axial map. In the second, we present the alternative models developed and a comparative discussion. In the third chapter, we build on the systematic comparison and elaborate on the idea that all models can be derived by the same Line-segment map and a different set of parameters. In the fourth, we introduce the experimental software tool for analysing multiple graphs using the same Line-segment map. In the final chapter, we discuss the methodological potentials of flexible Line-segment maps, the parametric representation of street networks and the open relationship between the ‘map’ and the ‘graph’, further.

2. URBAN MODELLING AND SPACE SYNTAX: THE CRITICAL ISSUE OF GEOMETRIC REPRESENTATION

Urban modelling concerns the fundamental relation between structure and process, where the physical environment generally constitutes the structure and human activity, the process. According to Wilson(2000), urban models are constituted by three components: some measure of attraction; some measure of distance; and some form of geometric representation of space. Recently, we have seen an important shift from location-based models, aiming to model the flow (people, goods, information) generated by the location of attractions, to flow-based models, aiming to model how the pattern of flows generate location (Batty,2013). This new emphasis has led to an increasing interest in representing cities as networks (Newman,2010), acknowledging that the pattern of connections between urban attractions influences flows and that this is essential for understanding both the performance of urban systems as wholes and the properties of their components. Formally, networks are described using graphs, which represent components by nodes and connections between components by edges; a simple notation that allows a wide range of phenomena to be represented as networks.

Space Syntax research has put great effort into the development of representations and demonstrates a long series of descriptive techniques (e.g. convex maps, interface maps, j-graphs; Hillier and Hanson,1984). With origins in architecture and aiming to study spatial form, Space Syntax models are concerned with structure rather than process. Even so, they are not simply representations of the physical environment, but rather of its affordances (Gibson,1986), that is, what emerges in the meeting between properties of the physical environment and human abilities of both physical and cognitive kinds (Marcus,2015). The Axial map is a fundamental example.

2.1 AXIAL MAP

The originality of the Axial map is found in its emphasis on human cognition in space. The Axial map is colloquially defined as the least amount of straight lines that cover all accessible urban space shaped by built form, where each straight line (axial line) represents an urban space that is possible to visually overlook and directly access. The Axial map takes the form of a network representation of urban space from the point of view of what we may call a cognitive subject, that is, a perceiving human being moving through space; where the network components are affordances related to human visibility and accessibility.

What distinguishes Axial map from typical urban network analysis is not only the conceptualisation of space represented by the axial line, as a form of ‘cognitive geometry’,

but also the shift in graph notation(Fig1). In typical representations street networks, such as the Road-centre-line maps, the geometric features are polylines representing street segments which span between street junctions. In the respective network graph, the nodes are the street junctions and the edges are the street segments(primal-graph); thus, putting emphasis to the points of route choice, especially important to traffic modelling.

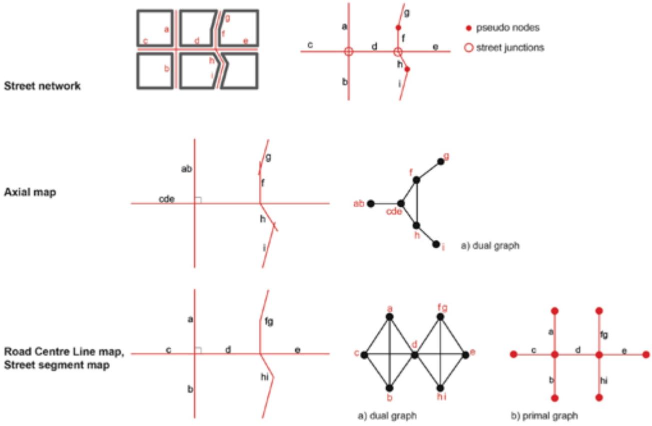

Figure 1 - Axial map and Road-centre-line map

Conversely, in the axial graph the nodes are the axial lines instead of the intersections between them (dual-graph). In this respect, the axial lines are not only the units of representation, but also the units of the analysis, creating a one-to-one relation between the 'map' and the 'graph'.

The analysis of the axial graph is based on measuring the topological distance from each node (axial line) to every other node in the system[1] and is related to typical network analysis. However, following the 'cognitive geometry' of the axial map, a topological distance of 1, not only represents a 'step' from one axial line to another; from the point of view of a moving subject it also represents a discrete change of direction.

3. ALTERNATIVE STREET NETWORK REPRESENTATIONS IN SPACE SYNTAX

In the past 15 years, alternative models of street network representation have been introduced in Space Syntax research. Although they are closely related to central tenets of Space Syntax theory and some can even be seen as variations of the Axial map, they do form discrete models in their own right. Moreover, they can be built on Road-centre-line maps and, thus, take advantage of greatly available ready-made GIS maps; a methodological step with looming advantages, especially regarding the feasibility of large scale analysis. However, researchers do not use and analyse Road-centre-line maps as they are; rather, they edit and manipulate them intentionally, to produce elaborate models of street network representation, in accordance with their particular viewpoints on environmental perception and cognition.

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[1] More precisely the 'distance' of the 'shortest' path between every pair of nodes

The models presented are:

1. Line-segment maps and Angular Segment Analysis (ASA), developed in Space Syntax research (e.g.Turner,2007; 2005; Hillier and Iida,2005; Hillier et al., 2012).
2. Natural Street maps, introduced by Jiang and Liu (2007); a model closely related to proposals from Figueiredo and Amorim (2005) and Thompson (2003)
3. Directional Distance model, introduced by Peponis et al. (2008)

They will be explored according to:

- the geometric representation of the street network
- the dual graph, on which the calculations are made
- the measures of distance they propose

3.1 LINE-SEGMENT MAPS AND ANGULAR SEGMENT ANALYSIS

The Angular Segment Analysis(ASA) has formed the main alternative to the Axial map analysis and is being extensively used by Space Syntax researchers. The analysis uses a Line-segment map, generated either from an Axial map, or from a Road-centre-line map. This paper will only focus on the second. The Line-segment map is produced by exploding the street segments, which are polyline features, to their constituent straight line segments; thus, a straight street segment is represented as one line, but a curvilinear one is represented as many lines following its geometry.

The graph of the analysis is constructed as follows:

- nodes: line segments
- edges: street junctions and pseudo nodes. Pseudo nodes occur where only two lines meet in different angles

ASA weights this simple graph by an angular cost. The analysis records the sum of angles turned from any origin segment to any other segment within the system[2] (Turner,2007). Hillier and Iida (2005) set the convention to translate actual angular degrees to values ranging from zero (no turn) to 2 (180°turn). This value is added to each graph edge as weight. A new measure of distance is here introduced; angular distance – or, as Hillier and Iida(ibid.) call it, geometrical distance – as opposed to the topological distance of the Axial map. ASA is implemented in various software (Depthmap, PST Place-Syntax-Tool[3]).Following the rule, a right angle turn (90°) is assigned a value of 1, matching the value which was assigned to each directional turn (step) in Axial map analysis. Moreover, collinear segments are assigned no angular cost (0°), becoming similar to axial lines (Fig2). This way, the Line-segment map seems to form a subtler variation of an Axial map. The segmentation of long axial lines makes the analysis subtler by measuring each segment individually, thus picking up differences in the density of intersections along a street. Also, by taking angular turns into account, geometrical properties, like sinuosity, are acknowledged. Moreover, it distinguishes between changes of great angular magnitude, such as right angle turns, and changes of a very small magnitude. However, there is a clear shift of focus from the topological to the geometrical properties of the street network. Furthermore, ASA steps from a purely topological graph to a weighted graph, thus changing its ontology.

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[2] following the shortest path between any pair of segments

[3] Mapinfo-plugin developed by KTH-School of Architecture, Chalmers University of Technology, SpacescapeAB,Sweden; to be available as QGIS-plugin

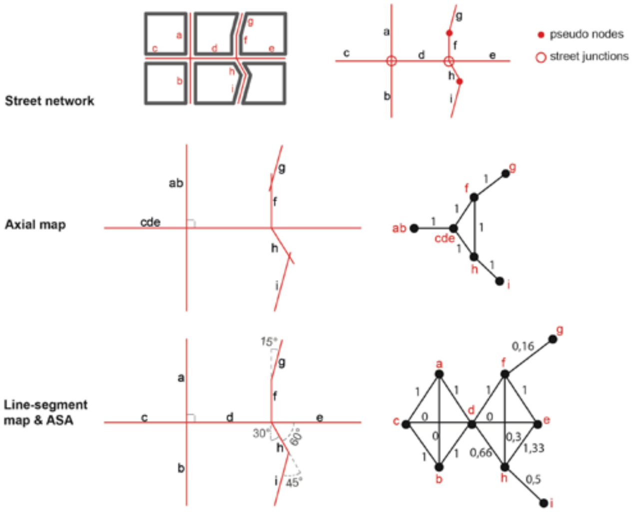

Figure 2.- Angular Segment Analysis and Axial map

The Line-segment map takes a rather undifferentiated approach to the street network. Graph nodes can be either actual street segments, or somewhat arbitrary fragments of sinuous streets; the latter often being an artefact of the digitization of the Road-centre-line map. Also, the graph edges can represent either street junctions or pseudo nodes; the latter again being arbitrary points of the mapping procedure. However, both are analysed as equal, although junctions are points of actual route decision; hence well-formed cognitive entities in relation to how we plan our journeys or give directions[4].

Related to that, the theoretical foundations of angular distance are still being formulated. Researchers use references from cognitive science to argue for importance of the angular turn (e.g.Turner,2007;Hillier and Iida,2005); and observational data showing that people tend to minimise angles toward their destination (e.g.Conroy-Dalton,2003). Still, one can't argue that it is the actual degrees of turn that influence human behaviour; nor that all angular turns, however small, are perceived by pedestrians, let alone drivers.

3.2 NATURAL STREET MAPS

Natural Street maps were introduced by Jiang and Liu(2007), building on previous work by Jiang and Claramunt(2002;2004). It is a street-based topological representation that was presented as an alternative GIS-based model to the Axial map. However, the concept of Natural streets is closely related to the concept of Continuity lines, introduced by Figueiredo and Amorim(2005) and to ideas of Thompson(2003).

The idea is that a street, however straight or sinuous, is a solid cognitive entity and should be represented and analysed as such; addressing the segmentation of curvilinear streets, typical in Axial map representation. Thompson(ibid.) early suggested that a curvilinear or sinuous street should be treated as a bent axial line and thus, keep its cognitive integrity. Figueiredo(2009) later proposed that instead of breaking curvilinear streets into many axial lines, we should

[4] We don't say “go straight, turn 3∞left, then straight, then 80∞left “; we say “take the first left”

consider them as Continuity lines, again arguing that they are generally recognised cognitive entities.

This idea is based on the good continuity principle, a concept introduced by the gestalt theory in the early 20th century psychology. This principle predicts the preference for continuous figures; the fact that we tend to group lines or curves that follow an established direction, over those representing abrupt changes in direction. Based on that, streets are naturally merged segments forming good continuities.

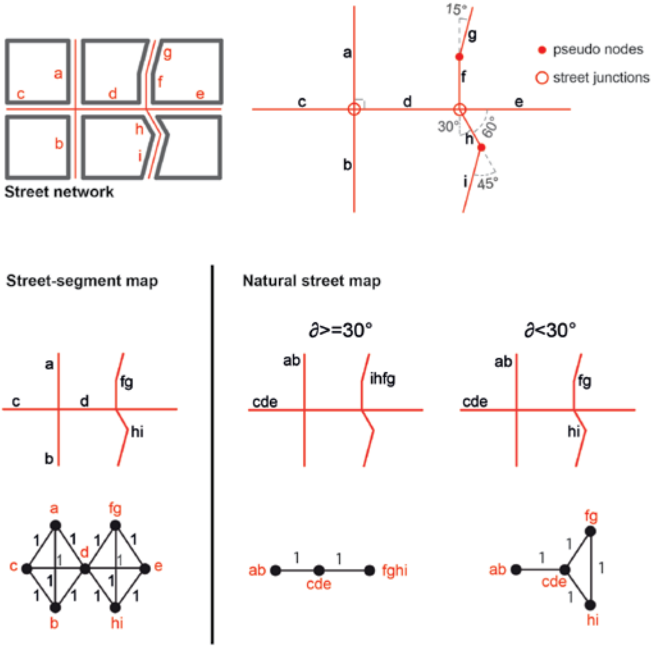

Figure 3 - Natural Street map

We will look more into Jiang and Liu's approach(Fig3). As they are working with Road-Centre-line maps, they introduced algorithms and parameters in order to merge street-segments into Natural streets, based on their continuities. The basic criterion is an angular threshold between the street segments, that should be applied to decide which segments are in good continuity and which are not. In each junction, a segment is concatenated to the adjacent one with the smallest deflection angle, provided that it meets the threshold criterion.

The continuous lines produced by that procedure are the nodes of the network graph. The graph edges are the line intersections. The graph is analysed using topological distance. The algorithms of the Natural Street model are integrated in Axwoman[5].

Jiang and Liu(ibid.) examined many angular thresholds ranging from 10∞ to 70∞. When applying large thresholds like 60∞, many streets are merged forming very long continuities. Jiang and Liu proposed that this approach would be more suitable for vehicle modelling

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[5] ArcGIS plugin software

which is more cognitive-based, memory-oriented and global in nature; whereas pedestrian modelling, which is more perception-based, visibility-guided and local in nature should use axial line representation. However, one can argue that such large-scale continuities would not form cognitive entities, even to a driver's mind.

3.3 DIRECTIONAL DISTANCE MODEL

Peponis et al.(2008) developed an analytical model of the street network, based on a new version of topological distance, called directional.

While starting with a straightforward line-segment representation, the dual graph produced is not that simple. Graph edges are not predefined; instead they are defined based on a parametric measure of directional distance. An angular threshold is introduced to define which direction changes will be taken into account in the analysis and which won't; any angular turn below or equal to the set threshold is not considered a change of direction, but a continuation(Fig4).

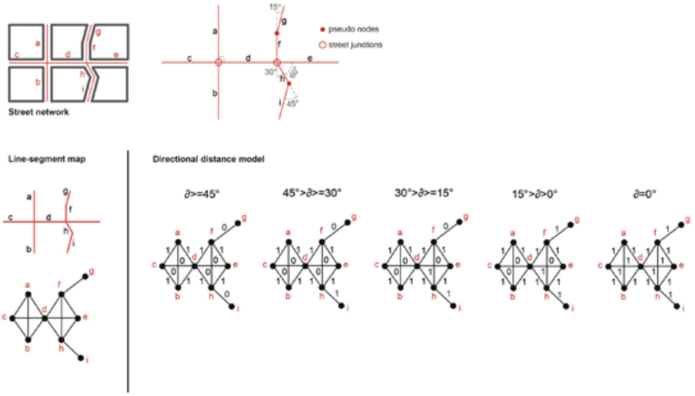

Figure 4 - Directional distance model

Hence, direction changes are treated as binary states; if they exceed the angular threshold they count as one(1) and if they don't, they count as zero(0)[6]. The authors argue '...we make no prior assumption about the existence of directional elements, or their perceptual or cognitive status. Also, we define direction changes parametrically, so that analysis can be arbitrarily sensitive.'(ibid.,p.899) The Directional distance analysis has been automatized in Specialist Lines software[7].

Their idea behind the parametrical definition of distance is that although changes of direction in general have been proven to be a fundamental element of the way people perceive and conceive the street network through movement, there is no proof that all changes of direction are perceptually significant; for example, we perceive quasi-linear streets as entities and not as a succession of fragments. However, instead of the angular distance introduced by the ASA model, they argue for the parametric definition of directional distance, as a necessary way to control the relationship between geometry and topology. It is clear that all of the above place extreme importance to the angular threshold chosen by the researcher; a specific number that defines which is the cognitively significant direction change and which isn't; a number that requires theoretical founding and empirical testing.

[6] A metric threshold is also added to the analysis, to account for curvilinear streets consisting of many short lines, where even a relatively sharp direction change can resolve itself into many smaller, that are below the threshold angle.

[7] also run in Grasshopper plugin

3.4 COMPARATIVE DISCUSSION: PARAMETRICALLY DEFINED REPRESENTATIONS OF THE STREET NETWORK

The different models present alternative approaches to the analysis of street networks; they produce different geometrical representations, they define the graph elements differently and they analyse the graph using a different concept of distance. However, they are all closely related to central tenets of space syntax theory; hence, they are different, but still comparable to each other and to the Axial Map. As Figueiredo(2015) has demonstrated, they could actually be described by the same Unified-Graph-Model; a unified representation of the street network that could adapt to almost any concept of distance.

What was already implied from Figueiredo's account, is that all are more or less parametrically defined; the ASA uses a weighted graph based on angular distance; the Natural Street model [8]uses angular thresholds to define the graph nodes; and the Directional distance model uses angular thresholds to parametrically define distance. They do not produce straightforward graphs that immediately relate to the representation, nor use a predefined set of graph elements, as did the Axial Map. There is a parametric definition of what counts as a node and what counts as an edge. Put differently, they parametrically redefine the relation between the 'map' and the 'graph', challenging the one-to-one relation between the two.

Following this idea, we argue that they can all be seen as parametrically defined representations based on Line-segment maps, the least aggregated representations of the street network. As will be shown, the same Line-segment map can produce all different graphs by using a different set of parameters.

4. LINE-SEGMENT MAPS AND A MULTIPLICITY OF GRAPHS

We compare the different geometric representations and their related graphs using a simple network(Fig5). What becomes evident is that what separates and identifies the different approaches can be essentially described with three interrelated questions:

- Which change of direction can be considered as cognitively significant?
- Are street junctions cognitively significant points in space, irrespectively of whether they lead to a change of direction?
- Are pseudo nodes cognitively significant at all?

These questions are answered differently by each model, leading to a different definition of which are the cognitive elements of the street network, and consequently, to a different definition of which are the basic elements of the graph; which are the nodes and which are the edges?

The Axial map considers all changes of direction to be significant[9]. However, it ignores street junctions if they don't lead to a direction change. This happens already in the drawing of the map. An axial line can transverse many street junctions if the street is linear, but a curvilinear street is usually broken in many axial lines, even when there is no street junction. All pseudo nodes are included in the graph, since by definition they lead to a direction change.

The Line-segment map, in its unweighted form, takes everything into account. All changes of direction matter and all street junctions and pseudo nodes are included in the graph edges. In the ASA, however, all changes of direction matter relatively to their actual angular change. That doesn't change the definition of the graph elements; it just weights the edges.

The Directional distance model builds on a simple Line-segment map, but then introduces an angular parameter to answer the first question. Changes of direction are considered significant as long as they are over a defined angular threshold.

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[8] Figueiredo uses Continuity maps as example

[9] In drawing Axial lines, very small angular turns are actually ignored, by tracing the longest lines of visibility.

The street-segment map in its simpler form doesn't care about changes of directions in curvilinear streets, so pseudo nodes are completely taken out of the graph. The significant points are the street junctions and only these count as graph edges.

Last but not least, the Natural-street model also introduces an angular parameter to define which street junctions will be included in the graph edges. Street junctions are ignored if they don't lead to a direction change over a specified threshold. Since, it is based on a street-segment map it ignores all pseudo nodes.

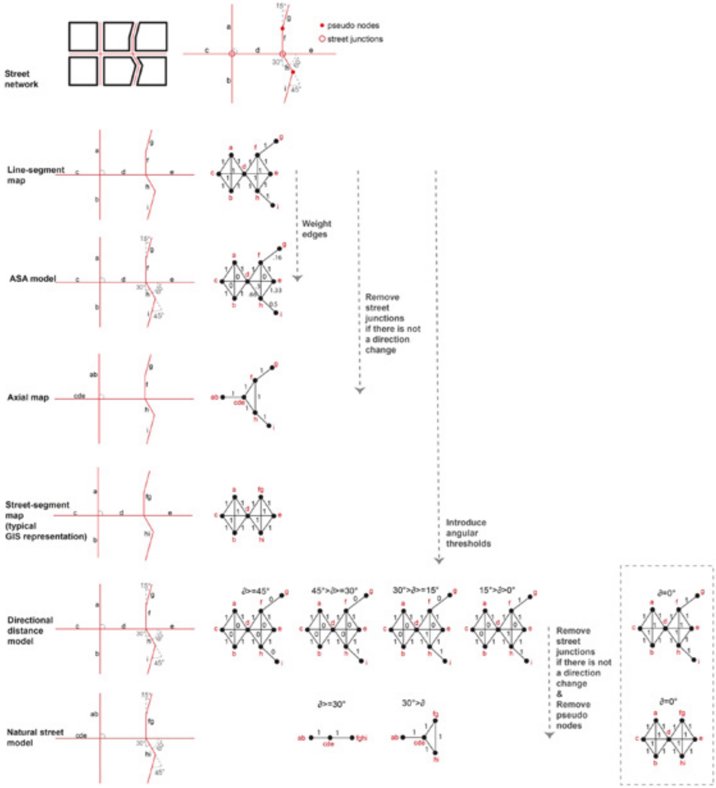

Figure 5 - Comparison and cross relations between graphs

It is evident that while the Axial map and the ASA model can produce one graph, the Directional distance model and the Natural-streets model can produce multiple graphs, by changing the angular threshold(Fig5). In an existing street network, which is far larger than the one used here, the results could be numerous.

A closer inspection reveals that the Line-segment map, produces the least aggregated graph and the Natural street map the most. What is also highlighted by the comparison of the graphs

is the cross relations between them. The line-segment graph can be transformed into the Axial graph if street junctions are not taken into account, when there is not a direction change; it can also be transformed into the street-segment map, if it ignores pseudo nodes. What is more, the Line-segment graph matches the Directional-distance-model graph, in the extreme situation of a zero-angular threshold; the Natural-street graph matches the street-segment graph in the same situation. The Natural-street graph can be transformed into an Axial graph if it includes pseudo nodes and with an angular threshold just above zero; enough to capture collinearity. A Directional-distance-model graph, can be transformed into a Natural-street graph, provided that an equal angular threshold is used; first, by removing all pseudo nodes and second, by removing street junctions when the direction change is below the angular threshold.

What is inferred from these cross relations is that starting from a simple unweighted line-segment graph - the least aggregated graph - all other graphs can be produced, just by introducing an angular threshold and including or excluding street junctions and pseudo nodes from the graph. What is consequently clear, is that with the same Line-segment map one can derive multiple graphs using a different set of parameters; parameters which are dictated by the stance each model takes regarding the cognitive and perceptual structure of street networks.

However, what is most important is not the fact that the multiple graphs described here can be produced using the same Line-segment map. What is important is that we realize how many more graphs could be derived with a given Line-segment map and a different set of parameters. The flexibility of Line-segment maps open immense methodological possibilities, which go beyond the specific models described in this paper. For example, one could easily change the angular parameters to follow the latest theoretical insights on human cognition, without having to change the map. But one could also imagine a completely different set of parameters and decisions that could lead to different graphs, related to alternative theoretical rationales.

5. EXPERIMENTAL TOOL FOR ANALYSING MULTIPLE GRAPHS USING THE SAME LINE-SEGMENT MAP

To exploit these methodological possibilities further, we developed an experimental tool as part of PST[10]. The tool inputs a Line-segment map and can modify the graph on the fly, based on two different options; following the described models. The user first chooses an angular threshold under which all changes of direction are ignored and are not considered as graph edges. Then, the user decides whether or not to include street junctions as graph edges, even when they lead to a direction change that is zero or below the specified threshold; meaning that street junctions are considered significant, irrespectively of the actual change of direction.

What is important is that not only the graph-edges, but also the graph-nodes change in the background of the analysis(fig6). Line segments are grouped on the fly, to form greater entities depending on the parameters chosen; these groups are the graph nodes. This background operation doesn't change the integrity of the original data and the original Line-segment map; the line-segments remain unmodified. Imagine, for example, three segments which, according to the parameters of the analysis, are considered continuous and are 'compressed' to form one graph node; in the output table, they remain separate features and get the same Integration value. In simple words, a Line segment-map is analysed as if it was an Axial map or a Natural street map and so on(fig7).

To make the modification of the graphs more transparent to the user, another function is added, which reveals the different formations of the graph-nodes, by colouring the different segment groups (Fig6,7). This function also makes the testing of the tool itself easier.

In Figures 6 and 7 we see variations of segment groupings depending on a different set of parameters. As we see, there are options which match a known model, like the Axial map or the Natural street map(Fig6), but also some new variations (e.g.Fig7:cases3,4). This happens because the tool does not include or exclude all pseudo nodes from the graph by a 'True' or 'False' choice. It includes only those which are above the given angular threshold; allowing for numerous variations of the graph.

[10] This experimental tool is implemented in the PST plugin to QGIS, developed by Chalmers University of Technology.

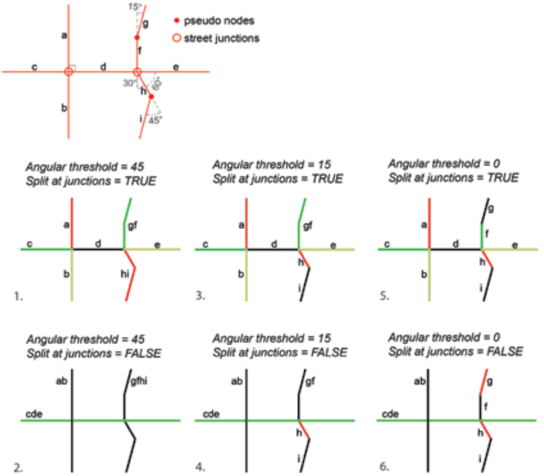

Figure 6 - Variations of a Line-segment map; segment grouping using different parameters.

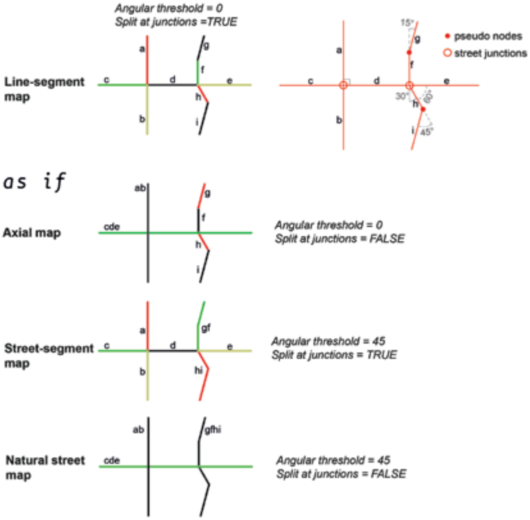

Figure 7 - Line-segment map analysed as if it was Axial map, Street-segment map, Natural street map

The experimental tool so far calculates Network Integration at different radii (steps or walking distance). Also, Node Count, Total Depth and Mean Depth are outputted in the results. One can run different analyses using a different set of parameters and the results of each calculation are written in the same table, making them easily comparable. The same map can of course be analysed using ASA in the conventional version of PST.

In Figures 8 and 9, there is an example of an existing street network and it is used just to demonstrate how the segments are grouped on the fly and how Integration results are outputted in the original map, depending on a different set of parameters[11]. The small area was picked because it includes both grid-like and more irregular network patterns. As expected, the differences are clear in both.

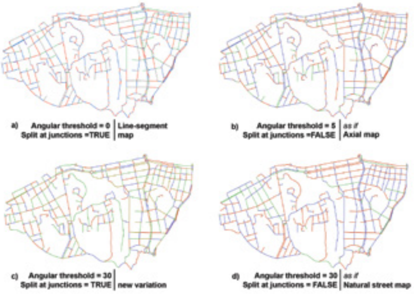

Figure 8 - Variations of segment groupings on the fly

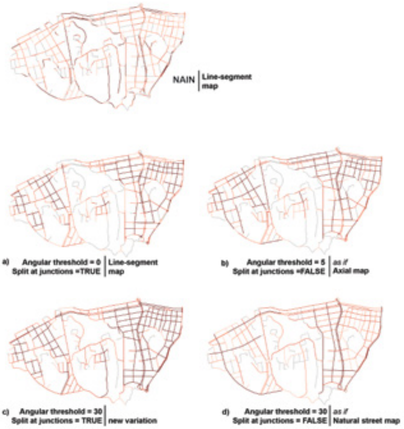

Figure 9 - NAIN and Network integration

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[11] As shown in Figure9b, in order to match the 'axial graph' an angular threshold of a little above zero is used. That accounts for the many small deviations between segments of linear streets, that are an artefact of the digitization of the Road-centre-line map. When drawing an Axial map such small deviations are ignored.

This investigation has not yet gone any further than to test the operational validity of the tool. We haven't reflected in depth on the results produced by the different parameters in the same urban area, nor have we tested against empirical data. These are further steps to be taken.

However, what is important in methodological terms, is that we can analyse the same street network from different cognitive and perceptual perspectives, using the same map. We can add and update results easily to follow the latest insights of cognitive science and environmental psychology. The map is 'augmented' to store all different approaches at all different times – in a way, to store past experience. Different rationales are embedded in one simple representation, in a way that can be easily comparable in a scientifically valid way. Moreover, the different variations can be comparatively tested against empirical data. Not least does this flexibility creates a great advantage in a phase where new measures are developed and thresholds and radii are tested.

6. FURTHER INSIGHTS

The value of the models described in this paper, goes beyond the question of whether or not they succeeded in offering a valid alternative to the Axial map, while using Road-centre-line maps in syntactic analysis. Perhaps it is too soon to tell; still a lot of empirical and theoretical validation might be needed. Their value lies in the fact that they enable different models to exist and to be used in syntactic analysis and that they challenged the one-to-one relation between the 'map' and the graph. Once they relativized this closed relationship by adding parameters, they opened up new methodological paths for future research.

It might not be as valuable to rush into looking for correlations to empirical data or for foundations in cognitive theory to either validate or disregard them. It is more useful to keep this discussion open, so we can exploit the potentials they created further. Should we look for one 'right' model for syntactic analysis or for a 'new' axial map; or should we explore further the possibility of Space Syntax analysis to be implemented in a multiplicity of representations and still keep its core theoretical principles? The development of these alternative models proves that it is possible. The experimental tool also presented in this paper is another step in that direction, allowing us to create and test different models using one single software.

The authors would like to thank dr J.Gill for his input in the early stages of this paper and M.Fitger for developing the experimental tool in PST.

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OPPORTUNITIES OF ARTIFICIAL NEURAL NETWORK GENERATED VGA

Training a Multilayer Perceptron to recognize the underlying structures of space

DÁNIEL SZEMEREY
University College London, London, United Kingdom
daniel.szemerey.15@ucl.ac.uk

SEAN HANNA
University College London, London, United Kingdom
s.hanna@ucl.ac.uk

AVA FATAH GEN. SCHIECK
University College London, London, United Kingdom
ava.fatah@ucl.ac.uk

ABSTRACT

This paper presents the research conducted with the aim of understanding if new advances in computer science, more specifically a type of supervised, feedforward Artificial Neural Network, a Multilayer Perceptron (MLP) is able to estimate the values of Visibility Graph Analysis (VGA) without the need for expensive calculation.

The overarching hypothesis is that an MLP can be setup in a way that it can be trained to learn the relationship between spatial configuration and the VGA (neighbourhood size and clustering coefficient) derived from it. Two hypotheses are stated: firstly, if such an MLP can be created than it will be able to generate spatial configurations for specific VGA values as inputs (mode A); secondly, the network would be able to generate VGA when presented with spatial configuration faster, compared to current method and with negligible error (mode B).

The hypotheses were tested by creating unique setups of an MLP for each mode, all of which had a different configuration. As each combination of possible setups were tested, the performance of the networks could be compared to each other and to the traditional method of VGA calculation.

Both mode A and mode B was able to achieve satisfying results that prove that an MLP is able to generate –with limitations- configurations based on VGA input and it is able to calculate the neighbourhood size and the clustering coefficient of a 2D layout substantially faster and with negligible error.

All MLPs were created at a generic space, therefore the MLP taught once can be adopted universally to most spaces. The implications of the two systems is that spatial analysis can be integrated into the design process, enabling interactive, instant analysis and the possible deployment of optimisation procedures, for instance a Genetic Algorithm.

KEYWORDS

Machine Learning; Visibility Graph Analysis; Multilayer Perceptron; Generating Spatial Configuration

1. INTRODUCTION

With the explosion of the computational power of personal computers we have for the first time adequate tools to understand the seemingly chaotic world around us. Through the combination of theoretical advances and new algorithms, designers reached a stage where they can predict the future through analysis and simulations far more accurately than it was previously possible. It is finally possible to understand Problems of Organized Complexity (Weaver, 1948).

Through the work of Bill Hillier, Julien Hanson and other colleagues (Hillier & Julienne, 1984) researchers can now begin to understand the complicated but close relationship between spatial configuration and human behaviour. Tools were developed to assist designers to carry out spatial analysis such as Axial Line Graphs or Visibility Graph Analysis (Al_Sayed, Turner, Hillier, Iida, & Penn, 2014).

However, as that these tools are crucial and they have been around for over thirty years, the question arises: What would be the effect if these tools were more accessible to the broader design community rather than just researchers? What would be the impact on early stage design, on the way we educate Architecture Students and on the way we generally look at spatial systems?

This paper aims to provide understanding if new advances in machine learning can be implemented to spatial analysis for it to be easier to understand and use.

The research problem

Methodologies developed for Space Syntax are implemented in software that requires a linear process of analysis: to create a design, feed it into a standalone software, wait for the analysis to finish, then evaluate the design and change it accordingly. This process requires, compared to the whole design period, a disproportionally large time and is not really viable in everyday practice.

Secondly, the processes involved in analysis is computationally heavy. They are also unidirectional, meaning that the current system cannot produce spatial arrangements according to desired analysis. It is possible to find a solution for both problems if we look at new advances in computational methods.

The human brain evolved to filter and process large amount of interlinked stimuli, such as understanding intricate scenery. On the other hand, computers are good in number-crunching 'human-hard' problems, such as precisely applying computational rules to a large set of data, but have difficulty in 'human-easy' problems, such as recognizing faces.

These barriers led to the birth of a new field of computer science, Artificial Neural Networks (ANN), that was founded on mimicking how the human brain might work (Mcculloch & Pitts, 1943). These new systems compute in parallel and are taught rather than given a pre-programmed set of rules (Flake, 2001), which means they are much faster and highly adaptable.

Multilayer Perceptrons are part of a unique set of ANNs. They are efficient systems that can associate two sets of correlated information, thus it is able to classify any new data it is given.

The main research question of the thesis is: *Can a Multilayer Perceptron understand the connection between a given spatial configuration and its Visibility Graph Analysis?*

This question has to be evaluated by testing the performance of the MLP created as part of the methodology.

Hypothesis 1: the MLP is able to 'understand' the underlying patterns in a data of spatial configuration and analysis and it is able to generate a 2D layout when given a desired analysis.

Hypothesis 2: the MLP is able to 'understand' the underlying patterns in a data of spatial configuration and analysis and is able to calculate a Visibility Graph Analysis faster than current methods.

Tool for early stage design

The creative process of Architectural Design has been often subject to change in the past century. In contrast to Gaudi's famous hanging models (REF), today's designer can have more iteration cycles before needing to physically building anything, as simulations speed up each cycle and still provide reliable results.

This shift towards early stage design is understandable, as with each new design phase the costs of change increases exponentially. Integrating analytical tools in the early stage design means minimizing the risk by complimenting the intuition of the designer with data.

There are three ways early stage design would benefit from a more efficient calculation of VGA.

Interactive Design

If the analysis would run hundred times faster, that would mean designers could get instant feedback on valuable VGA information during their initial steps of planning. Precedents of employing an interactive system for Architecture have been common, such as the use of interactive physics engine for form finding (Senatore & Piker, 2015).

As the designers are able to see instantly what a certain design decision result in, they can fix potential problems as early as possible.

Optimisation

With current methods VGA is of limited use in the fitness criteria of a Genetic Algorithm as it would need an uneconomically big computational power calculating the VGA of each individual of the population at each frame. Machine learning has been used to approximate models in similarly computationally expensive domains such as structural (Hanna, 2007) or aerodynamic (Wilkinson, Bradbury, & Hanna, 2015) simulation. A faster approximation of spatial analysis could similarly be used in the fitness criteria for the floor plan of a building.

Synthesis

Machine Learning has been widely used to synthesise solutions that would otherwise need a creative designer. David Cope's (1999) work on artificial music composition and Harold Cohen's (1984) work on algorithmic painting shows how creative programs can be. If an Artificial Neural Network was able to recreate the solutions that arithmetic VGA provides, then there is a possibility that the procedure could be reversed and the computer could provide design solutions for desired behaviour of people.

Teaching tool for Designers

Kinda al-Sayed research demonstrated, that a designer being guided by explicit knowledge (a factual knowledge that the person is aware of knowing) can "partially enhance their function-driven judgment producing permeable and well-structured spaces" (Al-sayed, Dalton, & Ho, 2010). As buildings are designed to enclose social interactions, it would be crucial for Architects to understand not just intuitively (without implicit knowledge) but explicitly the spaces they are designing. Making Space Syntax methods more interactive could be a way of improving Architecture Students ability to understand the quantitative connection between their design and social behaviour.

System Study

Artificial Neural Networks are parallel systems that process data at the local level but their output results in a global solution. There might have not been any connection between two points of the space during the calculation of the ANN generated VGA, however if the result is identical or similar to that of the traditional VGA, that would mean that the spatial system has properties of higher abstraction than that of simple numerical calculation of the graph.

This would explain why designers have an intuition on how people might move in a space without actually calculating quantitative properties of that space. As previously mentioned Kinda Al Sayed's work (Al-sayed et al., 2010) showed how learning factual, explicit knowledge improves the ability to design well-functioning spaces. An assumption to be made is that students learn these higher level structures of social behaviour in space during their studies.

Empowering designers

Current Spatial Analysis tools

'DepthMap' (new version: 'DepthMapX') was introduced by Turner and is the most widely used software for spatial analysis. It is able to do both Axial Maps and VGA analysis (Turner, 2001).

'SmartSpaceAnalyser' is a new add-on for 'Grasshopper' (a plugin for the popular software 'Rhinoceros') that performs instant analysis, but is not a competitor of 'DepthMapX' as it is unable to create neither Axial Maps nor VGA, just simple one location isovists (Happold, 2015). The advantage of it is that it is integrated in a CAD environment and can therefore give instantaneous feedback.

2. DATASETS AND METHODS

To handle the intricate relationship between any spatial configuration and its Visibility Graph Analysis (VGA), a Multilayer-Perceptron (MLP) was chosen as the core engine.

Such systems are taught by showing them a large number of labelled data samples, which can be considered as "cards" containing both the spatial configuration and its corresponding VGA. The network adjusts itself during the learning phase and thereby starts associating the expected VGA output with each plan. After training, the network would be expected to generalise to predict the output of plans it has not seen.

Firstly, a large dataset of cards was created, each card containing one pseudo-random arrangement of cubes on the same generic space and the VGA of that configuration. Secondly, the weights of the MLP are adjusted in the iterative process of showing those cards to the network. Thirdly, the system was tested and adjusted for better efficiency and validation (Fig. 1).

Two modes (A and B) were developed with the MLP. Mode A was taught so that if given a certain desired VGA outcome as input data then it will produce a solution to the configuration of the space. Mode B generates the VGA if a certain configuration of a space is fed in as input. The current paper only discusses Mode B in detail, Mode A is briefly shown.

2.1 CREATION OF THE DATASET

An MLP learns the regularities that exist in data shown to it. The larger and the more versatile the dataset is the more the network is able to understand global correlations rather than structure specific to a single data. In this section it is discussed how a large, inhomogeneous dataset was generated using Cellular Automata and multi-threading (Fig. 1).

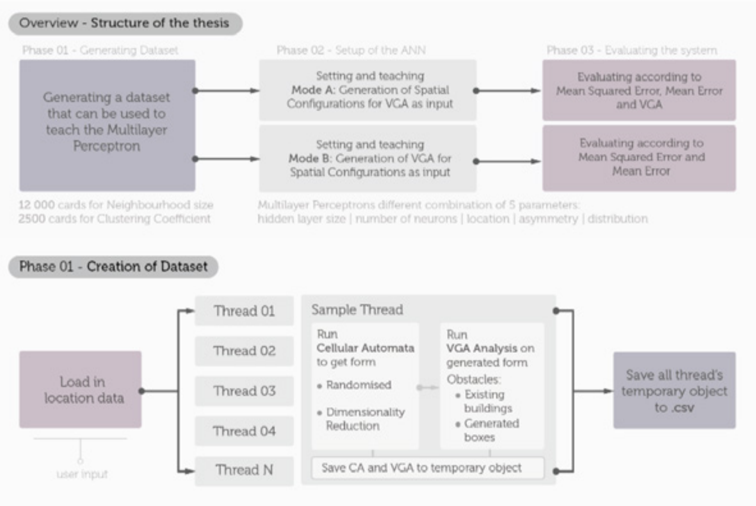


Figure 1 - Overview of the structure of the paper. Before teaching the MLP a variety of solutions have to be generated: different spatial configuration of the cubes and their VGA. This diagram demonstrates the process of creating the dataset.

Setup

The amount of cards the ANN has to be presented with depends on the resolution, but more data results in equal or better performance. For the sake of testing the systems presented here, 12.000 solutions were calculated, which were split into 10000 teaching cards and 2000 testing cards. The input for each is the spatial configuration, expressed as a grid in which grid squares are either on or off. The output is the resulting neighbourhood values or clustering coefficient values calculated by VGA.

As the process of calculating 12.000 VGA requires a substantial amount of time, the system runs solutions in parallel threads. Although it is assumed that the system created here will be universally adaptable (the designers don't have to teach their own MLP), the speed to uniquely tailor the network can be important. Each thread is run on one of the physical or virtual cores found on multi-core processors.

Each thread contains three processes: the first generates spatial configuration by running a Cellular Automata, the second calculates the VGA of the existing environment and the generated spatial arrangement. The third process stores the values in a temporary object that will be later written as a .csv file.

The area that is analysed has to be broken down into smaller elements for both the creation of spatial configuration and analysis. The values of the grid are shown in Fig. 2.

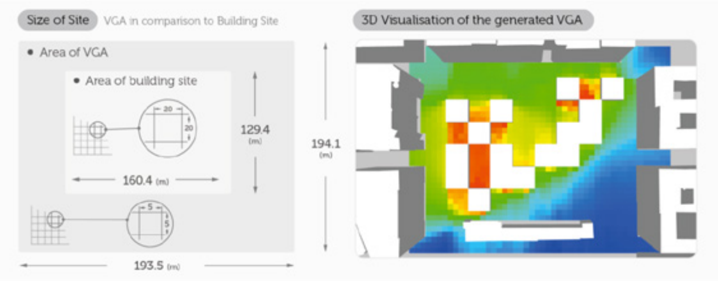


Figure 2 - Size of the area and of the grid for both the Visibility Graph Analysis (neighbourhood size) and the building site, where spatial arrangements are generated by placing boxes.

Generation of spatial configurations

The dataset has to consist of highly varied solutions, so that there is no bias towards one spatial configuration.

A grid of cubes was set up at the area of the building site. Each cube had a state of either up (1.0) or down (0.0). The initial grid consisted of 5 by 5 sized cubes, however a dimensionality reduction algorithm enlarges the cube size to 20 by 20. The area analysed in this thesis contained a grid of 6 * 8 boxes. For this reason, the number of possible states of the system is:

$$N = n_{states}^{\ n_{elements}}$$

$$N_{reducedSystem} = 2^{6*8} = 2^{48} = 2.81474977 * 10^{14}$$

The randomization process requires some form of generative process, otherwise if each cube's state is selected according to a probability it would result in a random noise of that magnitude. To tackle this issue a Cellular Automata was introduced that procedurally generate the spatial configuration.

Visibility Graph Analysis

To achieve the Visibility Graph, the given space has to be discretized into a fixed element size. For each element of the discretized grid the program checks if it 'sees' every other element. For this a double array of rectangle objects ('MyRect') is created, which store an Arraylist of 'MyRect' objects. Each time the program finds a rectangle that is visible to it adds that object to this Arraylist. The visibility at each cell of the grid is the size of the Arraylist. The clustering coefficient is calculated by implementing Turner's algorithm (Turner, 2001).

Each solution has a maximum and a minimum value of visibility. This is important as the values have to be mapped when fed into the MLP. The program records the local minimum and the local maximum of the solution and it also keeps track of those values between all the cards, which is the global range. During associative teaching the network has to understand these values in the global scale.

To tackle the problem of the edge effect a larger area is calculated and the edge are discarded.

Training the Multilayer Perceptron

After the dataset is generated an MLP can be created to test both of the hypotheses: to understand if it can generate spatial configuration based on VGA fed in as input Mode A has been created, to see if it is possible for the network to generate VGA based on spatial configuration Mode B has been explored. The method of how the MLP for each modes was set up is illustrated in Fig. 3.

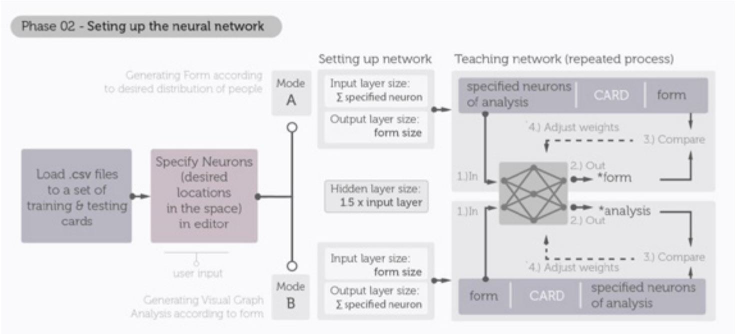


Figure 3 - How the Multilayer Perceptron was set up for Mode A and Mode B.

Once the required dataset was calculated and saved the data can be loaded into a set of teaching and testing cards, in the ratio of 5:1.

As the Neural Network uses a Sigmoid function when deciding if it should activate or not, all values fed into the network have to be mapped from -1 to +1.

Teaching the Multilayer Perceptron

An MLP is taught by showing it 'cards' that include two information: the spatial configuration form and its VGA. Every time a new card is presented as the input the system checks the difference between the output of the system and the solution on the card and adjusts itself by a pre-set learning rate.

Responding to inputs

The network is activated when all the output values of the neurons of the input layer are set. Then each neuron of the hidden layer calculates the weighted sum of the output of all neurons. The weighted sum is fed into a sigmoid function. The sigmoid function allows for a more continuous activation, thereby there is no drastic change between each state of the neuron during the learning phase. This model of the neuron is a modified version of the McCulloch & Pitts model, and can be written as the following formula. For each neuron:

$$y_i = sigmoid\ (\Sigma\ w_{ij}\ x_j)$$

Where y_i : the output of the neuron 'i' , w_{ij} : the weight of the connection between 'i' and 'j', x_j: the output of the input neuron 'j'.

After the output value of the hidden layer has been calculated the output of each neuron of the output layer is calculated. The inputs are now the weighted output values of the hidden layer.

Backpropagation

During the teaching process the weights are adjusted according to the difference of the network's output and the solution on the card. Each output neuron has an error that is the difference in value of its output and the value at the same location in the solution data. The error is multiplied by the steepness of the sigmoid curve at that location ('f(x)') to get the input value ('x') to the sigmoid function. It is also multiplied by a learning rate, which is needed to avoid local minima, as we are looking for global minimum.

The multiplied error gets then added to the weight. The same process is done for the hidden layer: the error values of the hidden layer's neurons are the sum of the errors of the output layer

multiplied by the weight (more connected neurons are corrected more). The weights between the input and the hidden layer are than adjusted as described for the weights between the hidden and the output layer.

General methods of evaluation

This project used three ways to measure the performance of each MLP. The sum of all the errors of each neuron summed up, the Squared Mean Error and for Mode A a comparison VGA. The mean squared error is used in order to 'punish' large errors more than small deviations.

Each error described for 'Summed Error' is first squared and then divided by 2. This means if the difference between the output of the network and the solution on the card is very high, then the Squared Error will be even higher than simply taking the error and for small errors, it will be smaller.

The sum of all neuron's squared error is calculated and divided by the number of possible errors: the number of neurons times the maximum possible error, the range (2) squared and divided by 2. This multiplied by 100 gives the percentage of Mean Squared Error.

MLPs can overfit the data, which means even though the performance of the network seems high, it has only learned local correlations in the dataset and fails on new data presented. For this reason, the performance of the networks was measured on 100 cards from a separated testing set to see if no overfitting occurred.

3. RESULTS

The MLP used in this project consists of three layers of neurons. There are two modes: A for generation of spatial configurations and B for Creating faster VGA (Fig. 4) .

The input and the output criteria are different for Mode A and for Mode B. These modes are described below in detail:

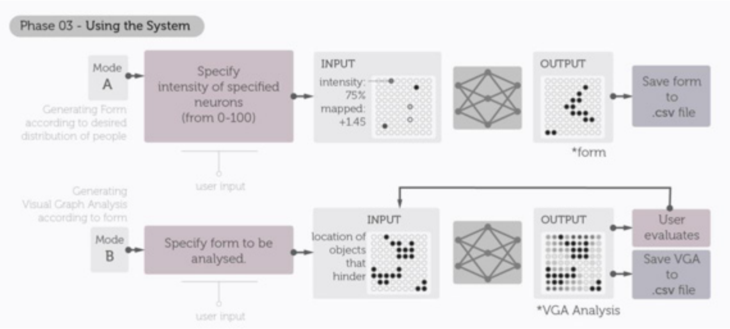


Figure 4 - Two different modes and how the network is set up and responds to in each case.

3.1 MODE B – CREATING FASTER VGA

Depending on how small the space is discretised and how big the analysed park is, the VGA could take from seconds to more than an hour. This makes the design-analysis paradigm very slow and hinders possibilities for analysis incorporated interactive planning or for optimization processes.

The aim of Mode B is that the network performance can come close or equal that of the original analysis, but offers a much faster process. Fig. 5 shows the visualisation of an example output results compared to the solution on the card.

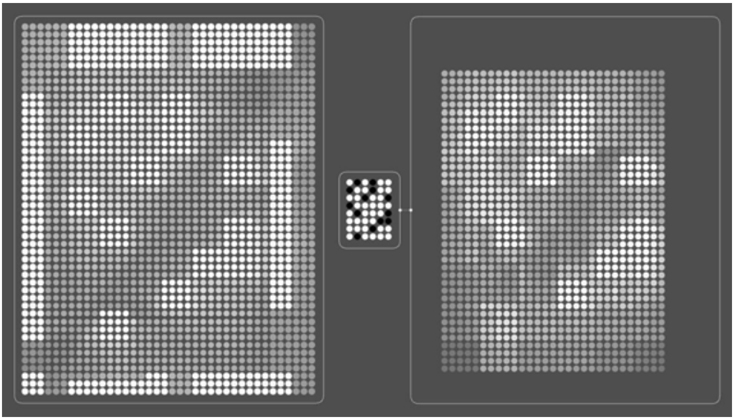


Figure 5 - MLP Generated VGA of Neighbourhood size. The space was divided into 5x5 networks.
Left: traditionally calculated VGA; Middle: Input spatial configuration; Right: MLP generated VGA

Possible design scenarios: Setup, Evaluation and Experiments

The MLPs input layer in this case are the values of the spatial configuration of the park and the solution to those inputs will be the VGA. Even though it is possible to specify location for Mode B, whereby only certain locations will be selected as outputs, it is presumed that users are more interested in using all locations to see the resulting analysis for the whole area.

To evaluate the performance of the system is straightforward for Mode B. Simply measuring the difference of the output of the network to the solution that is on the card. The performance is also clearly visible, as the input spatial arrangement should be clearly distinguishable on the output VGA, as those locations should have value 0 (shown as white). In the following various design scenarios are outlines and their performance are evaluated and discussed.

Experiments with a simple setup

Early experiments showed that setting a system up, that consisted of a lot of selected neurons, was not able to learn local differences: it clearly produced valid results for the perimeter area, as it was mostly high visibility, but shows constant white at the area of the boxes (Fig. 6).

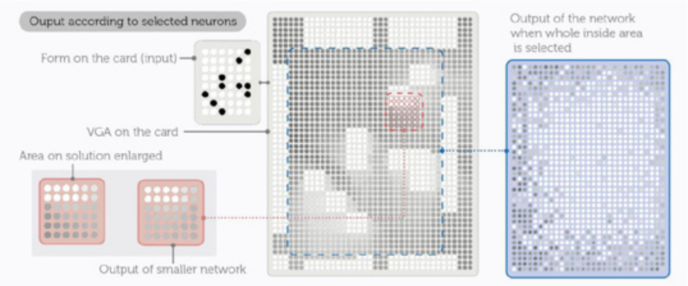


Figure 6 - Outputs of a network with only a small area selected and an output with the whole inside area.

It quickly became apparent that this is a problem originating from the amount of selected neurons. When only a small area was selected the network was able to produce valid VGA result below 1%(±0.14) mean squared error margin.

How it performs if network is separated in parts

A solution found to this problem was to divide the Visibility Graph Analysis into smaller areas, then a ANN is created for each of them. The input layer is always the same (the form) the output layer is one cell of the grid overlaid on the VGA.

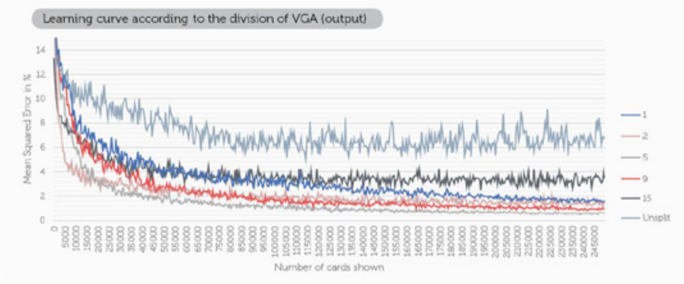
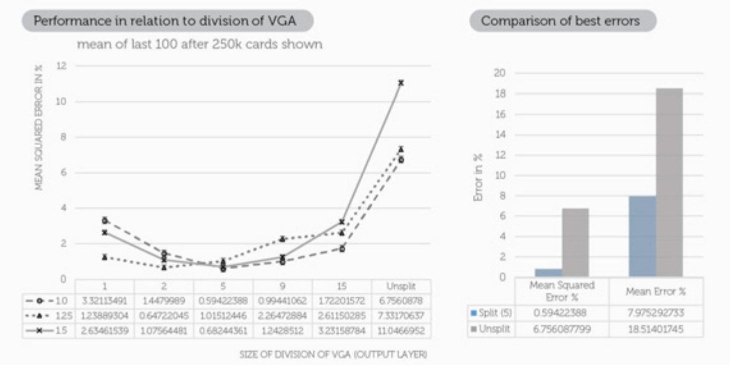


Figure 7 - Learning curve of six differently split systems.

Even though this procedure uses the input layer multiple times, the sum of all connections of the network is lower, as the size of the hidden layer is proportional to the output layer. These small networks can perform with less than 1% Mean Squared Error.

One question was related to the size of the overlaid grid. As Fig. 8 shows that the correlation between cell size and performance is not linear. The minimum of the curve is at cell size of 5 (meaning the grid consist of 5 x 5 cells). The reason this size performs the best is possibly due to the ratio of the cells sizes of the VGA grid to those of the boxes (also 5).



	1	2	5	9	15	Unsplit
1.0	3.32113491	1.4479989	0.59422388	0.99441062	1.72201572	6.7560878
1.25	1.23889304	0.64722045	1.01512446	2.26472884	2.61150285	7.33170637
1.5	2.63461539	1.07564481	0.68244361	1.2428512	3.23158784	11.0466952

	Mean Squared Error %	Mean Error %
Split (5)	0.59422388	7.975292733
Unsplit	6.756087799	18.51401745

Figure 8 - Performance of the system according to how big the cells are of the VGA overlaid grid.

Another surprising outcome is that the smallest hidden layer size performed the best in most cases. The ideal system for this dataset was a cell size of 5 with a hidden layer size that is equal to the output layer. Thus, this system can be very efficient, consisting of fewer connections. This will contribute to a faster system – both in terms of learning and in term of reacting.

The efficiency of each network

Fig. 9 demonstrates how much faster split networks are. Unsplit networks require nearly 50 minutes to teach 250 thousand cards, while the best teaching time for split network (5x5, 1.00 hidden layer multiplier) is less than 4.5 minutes (257 seconds).

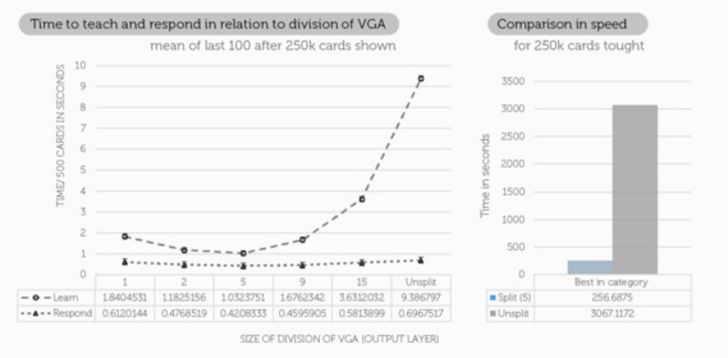


Figure 9 - Correlation between cell size of overlaid grid on VGA to time for the system to learn and to respond.

As the hidden layer is dependent on the size of the input the questions arises: would this efficiency of split networks persist even if the area of building size would increase? The answer is that VGA has always an equal or larger grid (smaller cells) than the spatial arrangement it is analysing, therefore the overall connections of split systems of VGA will always be lower than those of unsplit ones.

How it performs with Clustering Coefficient

The performance of the MLP was also measured for Clustering Coefficient, which is one step more abstract than neighbourhood size, as it is a measure of the resulting VGA. As Fig. 10 shows, the network was able to learn rapidly for all networks that were split.

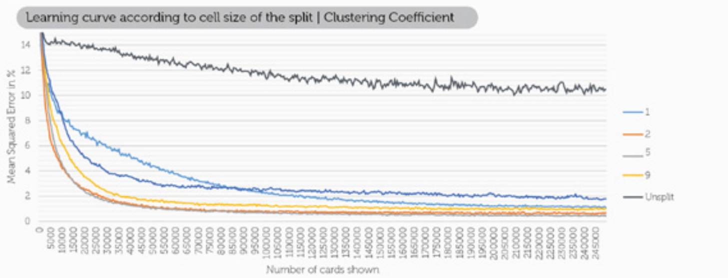


Figure 10 - The learning curve for Mode B when shown cards with Clustering Coefficient for different network splits.

How it performs in time compared to traditional method

The beauty of Artificial Neural Networks is that they are inherently a parallel computing system and can be easily multithreaded. The scope of this project didn't include the multithreading of the MLP, therefore a valid comparison is to measure both traditional system and the system created in this project on a single thread.

To calculate 10 VGA, the traditional calculation takes 40-50 seconds (about 15 seconds if run on multiple threads, while it takes less than 0.5 second to calculate it with the proposed system.

4. CONCLUSIONS

Three key characteristics describe the benefits of the proposed system.

Firstly, Artificial Neural Networks are able to calculate in parallel, which means the time it requires to calculate any solution is faster than methods developed for DepthMap. Although the accuracy of each system (shown in the result section) can not equal that of the traditional calculation, it is possible to set up systems for both Mode A and Mode B to achieve a negligible error margin (<1%).

Another key aspect is the system's universality. Even though a real public space was defined (Elisabeth Square, Budapest), both systems were also tested for generalised cases, which means they were set up and trained to just include a generic rectangular area on which spatial configurations were generated. This means the system only has to be taught once and it can be employed for any other space, therefore the computationally heavy and extensive process of generating data and teaching the network doesn't need to be repeated.

However, the system's limitation lies in its scalability. For cases when the resolution has to be finer for the same area or a larger space with the same resolution has to be analysed, than a separate network has to be used.

Lastly, the systems created are flexible. The reduction of the output layer doesn't influence the result of the calculation, so the system can be tailored for cases when only a smaller portion of the area needs to be analysed or generated.

4.1 MODE B

By splitting the discretised space into smaller areas the systems developed for Mode B, it was possible to generate VGA with high accuracy. As time is a crucial factor in the planning process, instantaneous analysis means that more design iterations are possible. Spatial analysis will also be used likelier, as accessibility is a key factor in adopting methodologies.

Speeding up the iteration also bring the values that a Genetic Algorithm (GA) or other multi-objective optimisation could integrate spatial analysis as an objective. Even though an optimisation algorithm could have implemented VGA as an objective with traditional calculation of VGA, it would run impractically slowly, as for e.g.: a GA has to evaluate immense amount of solutions to find the global minima of the fitness landscape.

During this project, an early prototype of an interactive system was created that shows how analysis could be embedded in the design phase, creating an interactive system.

Although Mode B allows for a faster calculation, the methodology of how to integrate it in a fitness function has to be worked out, more specifically what quantitative measure derived from the analysis should be taken into consideration. One suggested possibility could be to achieve a spatial configuration that has the highest visibility overall with the most built obstacles.

Further work

The MLP trained through the standalone programme could be tested with designers. The prerequisite is the integration of the trained network in an existing CAD environment (Grasshopper in Rhinoceros).

To see how far the methodology of this thesis reaches, other VGA measures, such as Mean Shortest Path or Point Depth Entropy have to be generated and tested. Axial Line graphs could be also shown to MLPs; this however would require a different methodology.

Another important question is whether the performances of these networks can be improved by introducing more hidden layers. These could be trained for combined measures to generate more types of solutions, for e.g.: along with clustering coefficient one could introduce parameters of building regulations, such as required distances between buildings.

5. CONCLUSION

This thesis set out to understand how a supervised, feedforward Artificial Neural Network, a Multilayer Perceptron (MLP) can be set up and taught to understand the underlying patterns of spatial configurations and their Visibility Graph Analysis (VGA). The aim was to provide a faster and more accessible tool for spatial analysis.

For this reason, two modes were explored: MLPs for mode A were created in order to generate spatial configurations for VGA as inputs, while the MLPs in mode B aimed to generate accurate VGA, both neighbourhood size and clustering coefficient.

The main contribution of the research is to show that space can be intelligible for an Artificial Neural Network and that current methods of calculating VGA can possibly be exchanged by MLPs.

More specifically the research found that for mode A a three-layer MLP was able to generate valid solutions, for specific variation of inputs. The main experiments were conducted for the purpose of understanding what properties of input arrangements influence the performance of generating solutions. A set of guidelines, such as symmetrical selection of inputs, were derived from these experiments.

Experiments for mode B came upon a method of creating MLPs that contribute to a substantial increase in performance, a decrease in teaching and in responding time. The main property of the method was to split the area into parts and create individual MLPs for each area.

To conclude, the thesis was able to take a step in a direction that if explored could yield additional improvement alternative methods of implementation for VGA and possibly for other Space Syntax methods, such as Axial Line Analysis.

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#176

EXTENDING SPACE SYNTAX WITH EFFICIENT ENUMERATION

Algorithms and Hypergraphs

ATSUSHI TAKIZAWA
Graduate School of Engineering, Osaka City University
takizawa@arch.eng.osaka-cu.ac.jp

ABSTRACT

In this research, we perform building-scale analysis, and the use of a convex map may be considered first. However, partitioning an architectural space is not easy, due to the ambiguity of the space. We believe that an analysis method to decompose the space with moderate granularity while considering its ambiguity is necessary. Hiller, for example, has been analysing space by convex polygonal coverings from before. However, these methods contain the NP-hard set cover problem. Based on this background, we propose a novel method that enumerates all patterns covering a relatively small space, such as a floor plan of a building with finite areas like convex polygons, and quickly extracts the optimum cover from them. The obtained cover is translated into a graph based on the concept of the hypergraph, and a method for calculating network features within it is proposed. We apply this method to the building-scale spatial data and examine the number of enumeration solutions, computational time, and network features of the obtained covering, etc. Finally, we show that the proposed method has excellent performance in these respects.

KEYWORDS

Set cover problem, convex cover, maximal clique, enumeration, hypergraph transversal computation, binary decision diagram

1. INTRODUCTION

Analysis methods of space syntax (Hiller and Hanson, 1984) include the axial map, convex map, isovist (Benedikt, 1979), and visibility graph analysis (VGA; Turner et al., 2001). They are used appropriately based on the scale of the analysis target. For example, the axial map is often used on a macro-scale, such as a street level, and other methods are often used on a smaller scale. In this research, we perform the building-scale analysis, and the use of a convex map may be first considered. However, partitioning an architectural space is not easy, due to the ambiguity of the space. In particular, in modern architecture, space partitioning tends to become ambiguous than before, and it is less likely that nodes can be clearly set like conventional convex maps.

Conversely, VGA analyses the space as a field of local points, rather than a space. Therefore, problems like the convex map do not arise. Conversely, because it is considered that designers and users recognize space as a region with a certain degree of unity, the granularity of VGA sometimes becomes too small. From the above discussion, we believe that an analysis method to decompose space with moderate granularity while considering its ambiguity is necessary. Hiller, for example, has been analyzing space by convex polygonal coverings for several years (Hiller and Hanson, 1984; Hiller, 2007). Covering elements allow partial overlap, but it is thought that the ambiguity of space can be considered to some extent. Moreover, because the axial map is a method of covering the space with a network of intersecting lines of sight, fundamentally similar ideas can be seen. Batty's method of covering with isovist (Batty and Rana, 2004) can

also be a method to structure the space with a covering. However, both methods contain the set cover problem. Because the set cover problem of a polygon is NP-hard (O'Rourke, 1983), it is not possible to find a solution in polynomial time. The heuristic algorithms, such as the Greedy algorithm is used in the algorithms of the axial map proposed so far (Turner et al., 2005; Poponis et al., 1998; Batty and Rana, 2004) and it has not been possible to obtain an exact solution.

Conversely, according to the idea of the maximum covering described later in the paper, the combination of coverings can be enormous. When considering such a property as ambiguity of space, it may become a new indicator that characterizes the quality of space. In addition, the development of recent discrete algorithm technology has been remarkable, even for NP-hard problems it is becoming possible to find optimal solutions and enumerate all solutions in real time.

Based on the above background, in this research, we propose a novel method that enumerates all patterns covering a relatively small space such as a floor plan of a building with finite areas like convex polygons, and quickly extracts the optimum cover from them. Currently, using the compressed data structure called a binary decision diagram (BDD; Bryant, 1986) and a zerosuppressed binary decision diagram (ZDD; Minao, 1993), we formulate the problem using some set operations of BDD and ZDD, focusing on the idea of hypergraph transversal computation. The obtained cover is translated into a graph, based on the concept of the hypergraph, and a method for calculating the network features within it is proposed. Finally, we apply this method to the building-scale spatial data and examine the number of enumeration solutions, computational time, and network features of the obtained covering, etc.

2. METHODS

In this section, we describe the proposed method.

2.1 TECHNICAL TERMS AND FUNDAMENTAL DATA STRUCTURES

A hypergraph H is a pair of (V, E) of a node set V and a hyperedge set E. Different from an edge of an ordinal graph, a hyperedge can hold more than three nodes in it. A transversal (or hitting set) for E is a set $T \subseteq V$, such that T hits every hyperedge in E, that is, $T \cap U \neq \emptyset$ for all $U \subseteq V$. A hitting set is minimal if no proper subsets are hitting sets. The transversal hypergraph of E is a hypergraph whose ground set is V and whose hyperedges are all minimally hitting sets for E. The hypergraph transversal computation, given a hypergraph, computes the transversal hypergraph by generating all minimal hitting sets.

A BDD is a graph representation of Boolean functions, which was introduced for an application of VLSI logic design and verification. Figure 1 illustrates an example of a BDD (and other decision trees). The node at the top is called the root. Each internal node has the three fields, namely V, Lo, and Hi. The V holds the index of a variable. The fields Lo and Hi point to other nodes, which are called Lo and Hi children, respectively. The arc to a Lo child is called a Lo arc and is illustrated by a dashed arrow. Similarly, the arc to a Hi child is called a Hi arc and is illustrated by a solid arrow. When a family of sparse sets is represented as a BDD, it is likely that there are many nodes whose Hi arcs point to F.

Minato introduced a variety of BDDs specialized for such set families, called a ZDD.

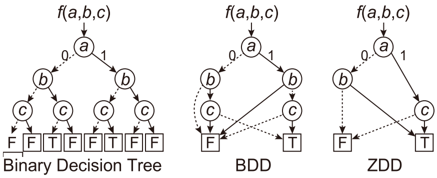


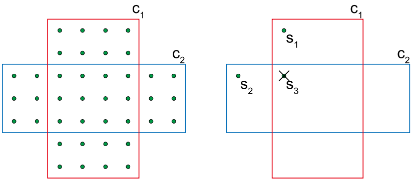
Figure 1 - Three kinds of decision trees expressing the same set of functions $f(1,0,1) = f(1,0,1) = T$

2.2 THE MINIMUM SET COVER PROBLEM FOR A SPATIAL POLYGON

Let P denote a polygon in Euclidean space R^2, allowing not only a simple polygon but also one with holes. We call a simple polygon $c \subseteq P$ a cover polygon and denote the maximum set of polygons as C . The maximum cover polygon is not completely covered by any of the other maximum cover polygons. The problem to be formulated is to enumerate all combinations of elements in C completely covering P. In addition, from among them, obtain the covering with the smallest number of the maximal covers and the largest area of them in dictionary order is also formulated.

In the above problem, it is necessary that one must judge whether P is completely covered. Considering this as a continuous geometric problem, formulation and implementation will become complicated. Conversely, in actual spatial analysis, it is often sufficient to generate discrete fine observation points in P as in VGA analysis, and check whether P covers all of them. Therefore, in this research as well, we formulate it as a problem covering all discrete points in P. Let S be the set of observation points in P. To enhance the accuracy of completely covering the area with discrete sampled points, we must generate points finely. However, it is not needed to use them all. Figure 2 illustrates an example to check whether the whole area of P is covered with two covering polygons $c^1 \cup c^2 = P$. While Figure 2a illustrates the whole set of S, we only need two points, e.g., $s^1, s^2 \in S$, as illustrated in Figure 2b. These points are included in c^1 and c^2, respectively. Meanwhile, if $s^3 \in S$ is selected, either c^1 or c^2 is selected because the point is included in both c^1 and c^2 and this is not the whole cover of P.

From the above discussion, we propose Algorithm 1. This algorithm checks the area containing each sampling point, and if the set of contained areas is the same as the other points already adopted, we discard the points and leave the necessary points (from line 2 to 9). Because the above part of the algorithm leaves points like s^3 , we eliminate them from line 10 to 13, where the $C'[0]$. pointset denotes the point set covered by the oth cover of oth and C'. coverset denotes the set of all covers for point s.



(a) All points (b) Necessary points except s_3

Figure 2 - Decimating sampling points.

Algorithm 1: Reduce to necessary points from all sampling points *S* for cover set *C*.

```
function ReducePoints, (C,S)
    $S' \leftarrow \emptyset$; $CS \leftarrow \emptyset$;
    for each point $s \in S$ do
        $C' \leftarrow \emptyset$
        for each point $c \in C$ do
            if $s$ is covered by $c$ then $C' \leftarrow C' \cup \{c\}$;
        if $C' \notin CS$ then
        $S' \leftarrow S' \cup \{s\}$;
        $CS \leftarrow CS \cup \{C'\}$;
    for each cover set $C' \in CS$ do
        if $|C'| \geq 2$ then continue;
        for each point $s \in C'[0].\text{pointset}$ do
            if $|s.\text{coverset}| \geq 2$ then $S' \leftarrow S' \setminus \{s\}$;
    return $S'$;
```

Then, we can formulate this problem as a typical set cover problem that each element of S´ is covered with the elements of C. Although the set cover problem is NP-hard, as described above, we can get the optimal solution using the latest mathematical programing solver if the problem size is not so large. However, in this study, it is necessary to enumerate all possible covers to add a new criterion on the diversity of a space. We formulate this problem as a hypergraph transversal problem. Now, we have sampling points $s_1, \dots, s_{10} \in S$ and covers $c_1, \dots, c_5 \in C$, as illustrated in Figure 3. Table 1 lists the set of covers for each point in Figure 3.

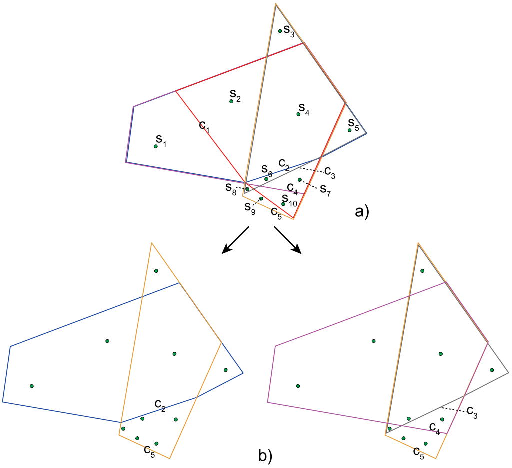


Figure 3 - An example of the minimum hitting sets: a) all cover elements and sampling points, b) all minimum hitting sets of a).

Let E denote the set of covers for each point. Then, we have a hypergraph $H=(C,E)$ where C is the ground set and E is the set of hyperedges. The subset of C that crosses all elements of E is a hitting set and its minimum is the minimum hitting set. In the example of Figure 3a, there exist two minimum hitting sets $\{c_2, c_5\}$ and$\{c_3, c_4, c_5\}$, as illustrated in Figure 3b. The problem with finding the minimum hitting set and the minimum covering is equivalent, and is similarly NP-hard. However, in recent years, some algorithms that can efficiently solve these kinds of problems of a certain scale have been proposed. In this research, we use the hypergraph traversal algorithm by Toda (2013), which is currently the most efficient algorithm. Because his algorithm uses BDDs and ZDDs as data structures, we describe how the problem is expressed with them. Each level of the node of BDDs/ZDDs corresponds to each cover in C. For example, the cover sets $\{c_1, c_2, c_4\}$ and $\{c_3, c_5\}$ that cover sampling points s_2 and c_3, respectively, in Table 1 are expressed by a ZDD, as illustrated in Figure 4. By adding the remaining cover sets in Table 1 to the ZDD, all covering elements for each sampling point are recorded in one ZDD and ZDD F, which is input data for Algorithm 2.

Sampling point	Set of covers for each point ($\in E$)
s_1	$\{c_2, c_4\}$
s_2	$\{c_1, c_2, c_4\}$
s_3	$\{c_3, c_5\}$
s_4	$\{c_1, c_2, c_3, c_4, c_5\}$
s_5	$\{c_2, c_3\}$
s_6	$\{c_1, c_3, c_4, c_5\}$
s_7	$\{c_1, c_4, c_5\}$
s_8	$\{c_3, c_5\}$
s_9	$\{c_5\}$
s_{10}	$\{c_1, c_5\}$

Table 1 - Sets of covers for each point in Figure 3.

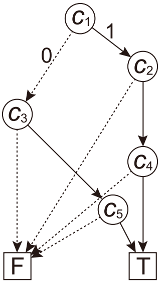


Figure 4 - ZDD expression of cover sets $\{c_1, c_2, c_4\}$ and $\{c_3, c_5\}$for sampling points s_2 and s_3, respectively.

Algorithm 2 enumerates all minimum hitting sets of F by using Toda's algorithm. This algorithm inputs a ZDD variable F, enumerates all hitting sets in line 2, reduces to the minimum hitting sets in line 3 and outputs them as a ZDD variable Z in line 4. The detail of functions Hit() and Min() is described in the appendix.

Algorithm 2: Enumerating the minimum hitting set of F.

```
1:  function EumMinHitSet (F)
2:      $B \leftarrow$ Hit (F);
3:      $Z \leftarrow$ Min (B);
4:      return Z
```

Then, we show Algorithm 3 that finds the cover having the smallest number of cover elements in Z with some efficient set functions that are implemented in the BDD/ZDD library we use. The class method of PermitSym(i) is a set function that extracts all combinatorial sets whose item size is less than or equal to Z in the ZDD variable Z, and returns them as a new ZDD variable. The class method Card () is also a set function that returns the number of items in the ZDD variable. This algorithm extracts the combinatorial set whose item size is just i in line 3 and outputs it if the size is greater than or equal to one in lines 4 and 5.

Algorithm 3: Find the set of covers with the smallest number of cover elements in Z

```
1:  function FindSmallestCovers (Z, C)
2:      for $i \leftarrow 1$ to $i \leq |C|$ do
3:          $Z' \leftarrow$ z. PermitSym(i) — Z. PermitSym(i—1);
4:          if $Z'$ . Card () $\geq 1$ then;
5:              return $Z'$
```

In general, Algorithm 3 returns a cover set having plural items. Among them, Algorithm 4 finds a cover with the largest total area of cover elements, where W[i] is the i -th element of a weight vector W, C[i] is the i-th element of a cover set C, and Area () returns the area of the cover. Chose_Best (W) is the class method that returns an item in the ZDD that maximizes the sum of the weight vector W given to each node of the ZDD. The area for each cover is given as a weight in line 3, the item that maximizes the total weight is extracted in line 4 and is returned in line 5.

Algorithm 4: Find a cover having the largest area in Z

```
1:  function FindLargestCovers (Z, C)
2:      for $i \leftarrow 1$ to $i \leq |C|$ do
3:          $W[i] \leftarrow C[i]$ . Area();
4:      $z \leftarrow$ Z. Choose_Best (W);
5:      return z
```

With the above-described series of algorithms, it is possible to enumerate all the minimal traverses covering all the sampling points, and furthermore to extract the cover with the smallest number of covering elements and the largest area among them.

2.3 THE MAXIMAL CONVEX POLYGON AS A TYPE OF COVER ELEMENTS

In the previous section, we formulated the problem into a general framework without specifying the type of covering element, but to perform the calculation, we need to specify the type. In this study, we adopt the maximal convex polygon as a type of covering element. Covering with convex polygons is general but an important way to structure space, as Hiller showed in his books (Hiller and Hanson, 1984; Hiller, 2007). That is, because any two points in a convex area are visible, a convex area is likely to be a basic unit of space. However, there exists various types of convex polygons. For example, the convex polygon A in Figure 5 is the one formed by connecting the vertices of obstacles. The number of convex polygons of this type is finite. Conversely, convex polygons such as B and C are of a type in which the end points of the convex polygons of a single store of obstacles do not coincide. Several such convex polygons can be made. Conversely, convex polygons such as B and C are a type whose (some) vertices do not coincide with the vertices of obstacles. Such a convex polygon can be made infinite, but they are perceived as unstable areas that are difficult for residents to recognize as a unit of space. Convex polygon D is called a s-partition, proposed by Peponis et al. (1997). The s-partition is made by extending the line segment of each obstacle's face and dividing the space with the intersection of the line and other wall lines as vertices. The s-partition is thought to have the effect of dividing the space into spatial units that are cohesive, to some extent, for residents and architects.

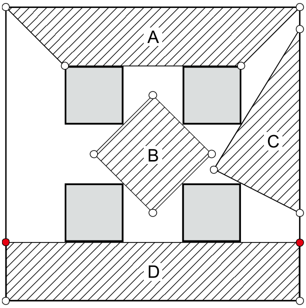


Figure 5 - Type of convex polygons in a floorplan.

From the above discussion, we consider both A and D types of convex polygons in this study. Algorithm 5 enumerates all maximal convex polygons as cliques whose vertex size is greater than or equal to three and outputs them as C. A clique of a visibility graph with greater than or equal to three nodes forms a convex polygon. For example, Figure 6 illustrates a visibility graph with a node set {a, b, c, d, e}. There exist five cliques whose node size is greater than or equal to 3; {a, b, c}, {a, b, d}, {b, c, d}, {c, d, e}, {a, b, c, d}. Among them, we have two maximal cliques {a, b, c, d} and {c, d, e} because other cliques {a, b, c}, {a, b, d}, {b, c, d} are subgraphs of {a, b, c, d}. Line 4 of Algorithm 5 enumerates all maximal cliques in G. Some efficient algorithms have been proposed to enumerate the cliques and we use Coudert's algorithm (1998), based on ZDDs.

Algorithm 5: Enumerate all maximal convex polygons as cliques from a floorplan polygon Z

```
function EnumerateMaximalConvexPolygons (P)
    Divide the wall of P into vertices and edges based on s-partition and let V be the set of vertices;
    Construct a visibility graph G connecting vertices visible to each other in P;
    Enumerate all maximal cliques C whose vertex size is more than three from G;
    return C
```

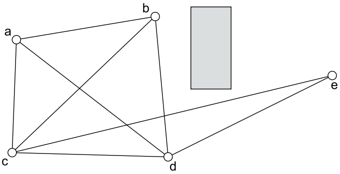


Figure 6 - Cliques in a visibility graph.

2.4 NETWORK CHARACTERISTICS OF A COVER AS A HYPERGRAPH

Next, we calculate some typical network characteristics for the cover. For that, we need to decide how to construct a graph from the cover. There can exist three methods to construct a graph. The first method is an axial map, where each cover element is regarded as a graph and each edge is drawn between each overlapped two covers. However, this method cannot consider the geometric characteristics of the overlapped area of the cover elements. However, although the value of the network characteristics of each node (cover) is generally different, this method does not determine which node's value should be adopted for the overlapped cover area.

Therefore, we partition the overlapped area. Figure 7 illustrates the partition of one of the maximal covers whose cover elements is $\{c_2, c_5\} = P$ in Figure 3. The polygon is partitioned into five nodes $\{v_1, v_2, v_3, v_4, v_5\} = V$. Here, we have two different approaches for constructing a graph. One is a general convex map where each two adjacent nodes are connected. The another is a hypergraph that (two or more) nodes in each cover element are regarded as elements of each hyperedge at the same time. In this study, we attempt the hypergraph modeling. We have the set of hyperedges $E = \{c_2= \{v_2, v_3, v_4\}, c_5= \{v_1, v_3, v_5\}\}$, whose node size is both three and the hypergraph $H=(V, E)$. Then, we calculate the mean depth and betweenness centrality in this hypergraph. Both measures require the shortest path computation. Because a hypergraph allows a hyperedge to have three or more nodes, the usual shortest path algorithm needs to be modified. Moreover, if the node size in a hyperedge is three or more, the network distance becomes shorter than that of a usual graph. For example, we now consider the shortest path from v_1 to v_5 in Figure 7. In a usual graph, it takes two paths because it passes through v_3. Conversely, in the hypergraph, it takes only one path because all those nodes are included in the same hyperedge v_5. We will discuss this effect and the meaning of hypergraph in the discussion.

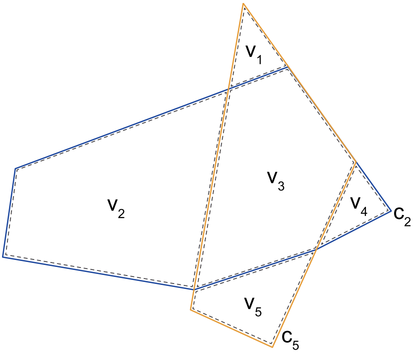


Figure 7 - Example of a hypergraph with cover partitioning.

3. VALIDATION AND RESULTS

In this section, we validate the method described in the previous section.

3.1 VALIDATION SETTINGS

We use the floorplan of the short-term treatment facility for emotionally handicapped children, that is designed by Sou Fujimoto. As illustrated in Figure 8a, the main characteristic of this architecture is that private rooms with squared shape are randomly distributed in space and various small and large open spaces are created in the gap. Those open spaces are not completely independent, but they are loosely connected with the surrounding other spaces, and their boundaries are ambiguous. The pitch of the sampling points is 10 cm. The specifications of the computer and compiler used for the validation are as follows: PC: VAIO Z (CPU: Intel Core i7-5557U, memory: 16 GB); operating system: Microsoft Windows 8.1 Professional x64; compiler: Microsoft Visual C++ 2015 (optimization option: Ox); BDD/ZDD library: Sapporo BDD in Graphillion (Inoue et al., 2016).

3.2 RESULTS

Figures 8b–g illustrate the process (steps b–g) and Figure 8h (step h) illustrates the validation result. In step b, polygon data is inputted. In step c, the polygon is s-partitioned and additional nodes are generated. In step d, a visibility graph is created by connecting vertices visible to each other, and the maximal cliques of the visibility graph are enumerated in step e. Then, we generate sampling points on the grid in step f and leave only necessary points in step g. Finally, by applying algorithms 2, 3, and 4, we find the optimal cover as illustrated in step h. As one can see, the relatively wide space located in the right-side of the floorplan is covered with a few large convex polygons. Meanwhile, many large convex polygons cover the wide space located in the left-side and it can be said that this space is more complex than the right space.

Because the main algorithm of the proposed method is one of enumeration, it is important to understand the scale of the problem to be solved and the computational time. Tables 2 and 3 list the size of the objects generated in each process and the computational time, respectively. The numbers that directly relate to the enumeration are the number of sampling points and the number of maximum convex polygons, which are 1,072 and 216, respectively. The number of enumerated minimal traverses is enormous. There is a minimum of 35 convex polygons to cover this space, but there are still 18,480 combinations of this. Conversely, the computational time is extremely short. It takes only 0.05 s for enumeration of maximal cliques, 1 s for enumeration of

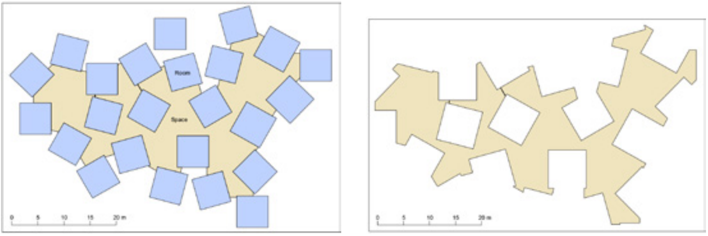
minimal traversal, and 0.01 s for extraction of optimal solutions, which is the central algorithm. The memory used is also about 70 MB at maximum. This is an effect using BDD/ZDD which are compression data structures, and it may be impossible by the usual approach without compression.

Objects: polygon, graph or set	Size
Original floor plan polygon	93 (node), 93 (edge)
Additional nodes by s-partition	86
The visibility graph	179 (node), 1,728 (edge)
All maximal cliques	219 (all), 216 (except for type B and C polygons in Figure 6)
Sampling points	57,306 (all), 1,072 (necessary)
All minimum hitting sets	1,543,606,641,113,586,432
Convex polygons with minimum elements	35 (num. of elements), 18,480 (num. of combination)
Convex polygons with maximal elements	64 (num. of elements), 264,925,440 (num. of combination)

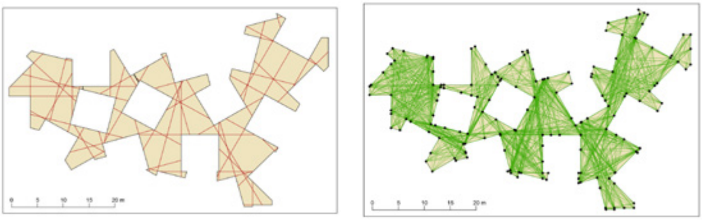
Table 2 - Size of objects generated in each process.

Step	Computational time (sec)
File input, s-partitioning and constructing a visibility graph	1.3
Enumerating all maximal cliques in the visibility graph	0.05
Generating sampling points	2
Enumerating all minimum hitting sets	1
Finding a cover with the smallest number of elements and largestarea	0.01

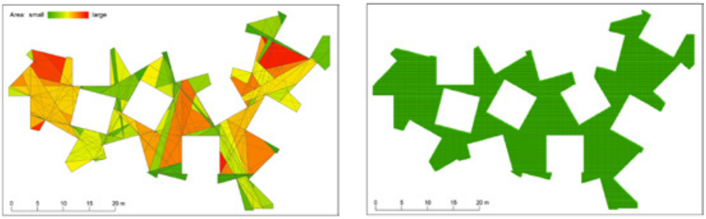
Table 3 - Computational time of each step of the example.



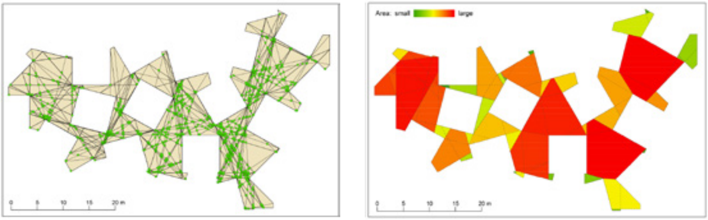
a) Floor plan b) Part of the open space of a)



c) S-partition d) Visibility graph



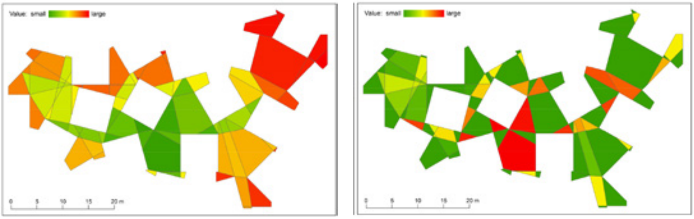
e) All maximal covers f) All sampling points



g) Necessary sampling points h) Final cover

Figure 8 - Validation process of the proposed method with the target floor plan.

Figure 9 illustrates the graph characteristics proposed in 2.4 applied to the cover of Fig.8h. It is common for the average depth to be shallow in the central part of the space and deeper in the peripheral part, but when looking closely, there is a point where the monotonicity of the depth is reversed in the overlapping part of polygons. This is due to using hypergraph as described above. This tendency is more pronounced in betweenness centrality, and its value tends to be higher at the overlapped node than at the center of a large space.



a) Mean depth b) Betweenness centrality

Figure 9 - Distribution of the network measure in the final cover.

4. DISCUSSION

As explained earlier, since the network characteristics by the hypergraph is different from that of the usual graph, it is necessary to discuss how to evaluate it. Recent research on space syntax is increasingly distinguishing between indicators by visibility and movement. Because a hypergraph allows to include more than two nodes, it does not necessarily have to go through spatially adjacent nodes. Due to this nature, it can be said that hypergraph is a suitable method for modeling the network of visibility. In the first place, what does it mean to model the connection of space as a hypergraph? For example, an axial map models the line of sight as a node, regards the intersection with other lines as an edge of a binary relation, and segments the space as a normal graph. Therefore, the edge does not include information beyond the adjacency relation. On the other hand, the proposed method creates a hypergraph by partitioning covers into nodes and using the original cover as a hyperedge. Therefore, what corresponds to the line of sight of the axial map is modeled as a hyperedge rather than a node. Since hyperedges and nodes have geometric information, it can be said that the proposed method can graph the space preserving rich information, in a sense, than the axial map. In the future, it is necessary to verify with actual spatial cognition and behavior.

As another issue, since this research deals with enumeration problems, it is necessary to grasp to what extent the problem can be solved. The size of the polygon targeted in this study is about 100 nodes at most. However, for example, in the case of Gassin's data which is often used in the study of space syntax, the number of nodes exceeds 1000 points. When we enumerated it with this data, enumeration was impossible. In the case of problems of this scale, enumeration has to give up, but if we formalize as an aggregate covering problem and only find an optimal solution, using the current mathematical programming solver can solve it in a practical time sufficiently. In the future, it is necessary to investigate the calculation limit of the proposed method in detail.

5. CONCLUSIONS

In this research, we point out the problems of a kind of spatial analysis method that covers the space represented by Axial Map in the analysis methods of space syntax. As a new analytical method, we proposed algorithms of enumerating all covering patterns of space based on BDD / ZDD and algorithms of extracting optimal solutions. Then, we also proposed a method to obtain the network characteristics of the obtained covering based on the concept of hypergraph. As a result of verification of the proposed method with the floorplan of the short-term treatment facility where the number of nodes is about 100, it was possible to obtain enormous enumerated solutions and strict optimal solutions very fast with small memory. We found the network characteristics of the optimal solution and found that the value becomes relatively high mainly at the intersection of the cover. Future tasks include verification of the method in various spaces, understanding the spatial scale which is the calculation limit of the enumeration algorithm, development of new spatial features making full use of enumerated solutions, verification of spatial features by hypergraph etc.

ACKNOWLEDGEMENT

This study was supported by a Grant-in-Aid for Scientific Research (C) (No. 16K06652).

APPENDIX

The algorithms of Hit(p) and Min(q) proposed by Toda(2013) are listed below, where Lo(p) and Hi(p) returns Lo node and Hi node of node p respectively, V(p) returns the index of node p, and BBD_Unique(k, l, h) and ZDD_Unique(k, l, h) respectively return a unique BDD / ZDD node associated with a key(k, l, h) as illustrated in Figure 10, And(a, b)returns the product set of sets a and b, Dif f(a, b) returns the difference set obtained by subtracting b from a.

Algorithm 6: Given a ZDD p, compute the BDD for all hitting sets

```
function Hit(p)
if $p=T_Z$ then return $F_B$;
if $p=F_Z$ then return $T_B$;
hl ← Hit(Lo(p));
hh ← Hit(Hi(p));
t ← BBD_Unique (V(p), hh, $T_B$);
q ← And (hl, t);
return q;
```

Algorithm 7: Given a BDD q, compute the ZDD for all minimal sets

```
function Min(q)
if $q=F_B$ then return $F_Z$;
if $q=T_B$ then return $T_Z$;
mh ← Min(Hi(q));
ml ← Min(Lo(q));
t ← Dif f (mh, ml);
r ← ZDD_Unique (V(q), ml, t);
return r;
```

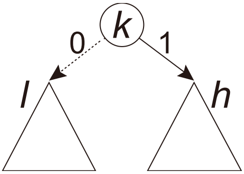


Figure 10 - Image of BDD_Unique (k, l, h) and ZDD_Unique (k, l, h).

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WHAT IS THE EXPLANATORY POWER OF SPACE SYNTAX THEORY?

The application of modal logics from theory of science

AKKELIES VAN NES
Faculty of Architecture, TU-Delft, The Netherlands & Department of Civil Engineering,
Western Norway University of Applied Sciences, Norway
a.vannes@tudelft.nl and avn@hvl.no

ABSTRACT

This contribution shows various approaches from the theory of science for revealing the explanatory power of the Space Syntax. In this contribution Bhaskar's critical realistic model of science and Georg Henrik von Wright's account of *explanation* and *understanding* are used to assess the explanatory power of Space Syntax research. In essence subsequent considerations distinguishes between a theory able to offer an *explanation* of phenomena and a theory proposing an *understanding* thereof. It will lead to the conclusion that the theory of the natural movement effect can offer an explanation of changes in a built environment in terms of cause and effect, while research related to social rationality, archaeology or historical research, space and crime or anti-social behavior, cognitive aspects aims at an understanding of the culture or meaning associated with the causes at issue. Moreover, research concerning how activities in society affects urban space requires a hermeneutic approach, whereas research concerning how a spatial layout can affect activities in society requires both a positivistic as well as a hermeneutic approach. Seemingly, human behaviour as an effect on spatial structure depends on the type of rationality of human intentions and behaviour the research is focusing on. Marked rationality can use positivistic explanation models, whereas other kinds of rationality rely on hermeneutic ones.

KEYWORDS

Theory building, modal logics, positivism, hermeneutics, explanations, Space Syntax theory

1. INTRODUCTION

In what ways are theories on built environments able to explain certain kinds of urban changes? Are they able to predict future effects of recent urban changes? Or are they confined to offering an understanding of according phenomena? At present the challenge for Space Syntax is to make proper theories (Hillier 2013). Whereas Hillier approaches theory building on Space Syntax from a social anthropology angle (Hillier 2016), other authors approach it from an urban sociology perspective (Marcus 2015, Koch 2015, Griffith 2015). Hillier's main question is what are cities for? His answer is to create contact. Therefor the challenge is to *explain* or to *understand* the spatial factors shaping opportunities for creating contact.

Building systematic theories on built environment is still in a beginning phase. The reason is that most writings on built environment tend to have a *normative* approach (Hillier and Hanson 1984, p. 5), where the authors describe *how* to make a good city. What is lacking is a description on what a good city is or how a city *function* spatially and in relation to society. Conversely, writings in the field of urban sociology lack concise definitions of space or understandings on the physical framework on where various social interactions take place. During the last two decades, computer developments have made it possible to work with large amount of big

data and with whole regions. Several empirical based research projects are carried out the last decade.

If a discipline is lacking a theory or the theory is not proper developed, then one starting point could be from the elementary theory of science. My contribution is to approach theory building on built environments through the use of Georg Henrik von Wright's modal logics combined with Roy Bhaskar's models on how research can be described on "think", "see" and "is" levels.

Any explanation of urban changes requires identifying their causes. For this purpose it is necessary to identify intended and unintended effects of proposed plans, to describe in detail how cities actually are built up and work, i.e. how they function, and finally what their different elements mean. Research on the setup of built environments depends on answers to these questions.

The first part of this article will present different ways of perceiving reality in a scientific perspective. For this purpose it is useful to turn to Bhaskar's critically realistic model of science first. In this article's second part, the explanatory power of the theory of the natural movement economic process and the theory of the natural urban transformation are revealed. Likewise, the explanatory power of space syntax research related to socio, historical or cultural issues will be revealed. As will turn out various research approaches with the application of Space Syntax use different models of casual explanation. Finally, a discussion of limitations and challenges of theory building in Space Syntax will be appropriate.

2. THE CRITICAL REALISTIC VIEWPOINT

As any research investigations on the built environment presupposes a general account of the ways one *perceives* and *thinks* of reality and what it actually is. Bhaskar distinguishes three levels research has to account for. The first level is labelled the "is" level, concerning reality in so far as one intends to know about it, to understand it, and to predict its further course. The second level is the "see" level, dealing with the perception and observation of reality. But likewise the application of scientific theories to gather accurate information about reality is at issue. The third level is the "think" level, comprising notions, ideas and thoughts about reality. Fig. 1 presents basic interdependences between these three levels (Troye, 1994, p. 33). According to Bhaskar, these three levels are interrelated with one another in four different ways. He proposes the following four epistemological attitudes based on the above-mentioned three levels:

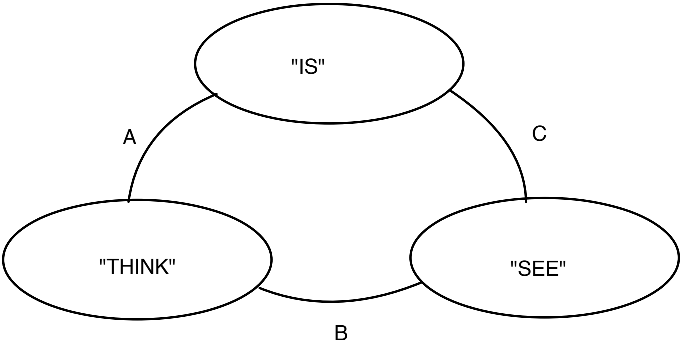


Figure 1 - Three levels for describing research

Rationalism: The researcher as thinker

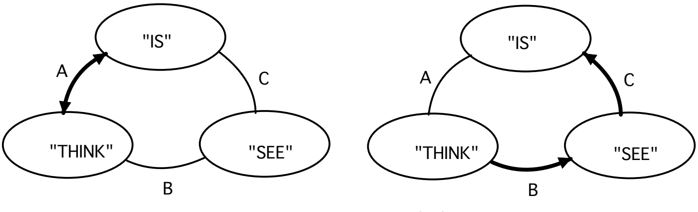
Idealism: The researcher as inventor and creator

Empiricism: The researcher as observer and discoverer

Realism and critical realism: The researcher as critical thinker, inventor, and discoverer

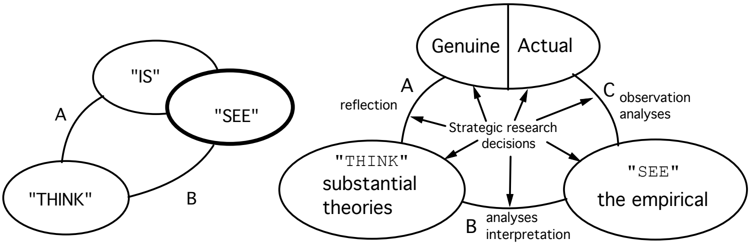
Rationalism obviously favours thought. Here research sets out from concepts of the built environment, its structures and order. In this perspective reality is a conceptual issue. Observation receives little attention. The canonic example of rationalism is Cartesian philosophy, often labelled by Descartes' thesis "Cogito ergo sum" (Troye, 1994, p. 34). The thick line *A* in figure 2 from the "think" to the "is" level is meant to indicate this stance.

An idealistic view implies that the idea one has about a phenomenon is part of reality. In Hegel's idealism for instance, reality gets transformed in terms of speculative ideas about it. The ideas one has e.g. about elements of a built environment are a forming part of it. In an idealistic sense the acknowledgement of truth does not just result from observation, but is also due to the scientist's grasp and vision of reality (Troye, 1994, p. 36-46). The thick lines *B* and *C* in figure 2 from the "think" to the "see" and further to the "is" level illustrate this stance.



A rationalistic perspective

An idealistic perspective



An empirical perspective

A critically realistic view

Figure 2 - Various types of perspectives

An empiricist epistemology mostly presupposes that reality is conceived in terms of the observer's perceptions. While reality is not in a sense directly accessible for the rationalist or the idealist, truth in the empiricist sense finally results from the perceptual data the observer manages to receive (Troye, 1994, p. 46-55). As shown in figure 2, this stance is illustrated by conflating the "see" and "is" levels.

Realism and critical realism include aspects of all the three above-mentioned models with the purpose to account for the development of scientific theories. This stance implies that theory development has both rationalistic and idealistic stages, where searching for empirical support. Reality, as presented on the "is" level, is divided into two parts: a genuine and an actual one. The genuine part consists of structures and systems that cannot be seen, while the actual one consists in ways in which reality presents it-self in observation and experience.

In comparison with the three other models of a basic epistemological stance, the critically realistic model has a major advantage. It is sufficiently comprehensive to account for the internal development of scientific theories and according research. How to use this model to acknowledge theories as being appropriate for research on built environments?

Various Space Syntax research fit into Bhaskar's critically realistic model. However, this model scarcely allows for an assessment of a theory's explanatory power. But associating von Wright's concepts of explanation and understanding with Bhaskar's critically realistic model, allows discussing the explanatory value of various types of Space Syntax research. As will turn out, it is their difference in explanatory power that requires acknowledging them as belonging to different scientific traditions. In this contribution the explanatory power of the different kinds of statements need to be set forth. As it turns out, Space Syntax is able to explain changes in urban space and changes in flow of movement and economic related activities and to understand cultures, human behaviour and cognitive factors related to urban space.

3. THE EXPLANATORY POWER OF STATEMENTS

From the theory of science, Carl Gustav Hempel's classical deductive-nomological explanation model is set up as follows (von Wright, 1971, p. 10):

Explanandum: The phenomena or facts that have to be explained

Explanans: The conditions affecting the phenomena or facts to be explained, and the general laws and explanation principles

Explicatum: The explained phenomena or facts

This explanation model does not mention any concepts of cause and effect (von Wright, 1971, p. 15). However, von Wright has clarified the notion of casual explanations in a way sufficiently clear for the present purposes. Casual explanation models are dependent on two epistemological traditions of scientific methods, namely the positivist and the hermeneutic tradition. Both these scientific traditions impose different structures and conditions on their causal explanation models. The way these models are built up depends on how according theories are set up, and on the way they are able to use these models to explain particular phenomena (von Wright, 1971, p. 1-4).

The positivist tradition emphasises the identification of the causes of certain phenomena. Due to this methodological option according theories account for the effects of causes with a high degree of *predictability*. Their explanatory models anticipate nothing but the effect of certain kinds of causes (von Wright, 1971, p. 3). The hermeneutic tradition emphasises explanations that search for an *understanding* beyond the phenomena. They aim at intentions implicit in the explanandum part of Hempel's model (von Wright, 1971, p. 4).

Von Wright bases his causal explanation models upon the concept of a precondition he prefers to the notion of a functional condition. Obviously, he distinguishes between *necessary* and *sufficient* conditions. The usage of these kinds of conditions regulates as to whether the causal explanation model is applied to a hermeneutic or a positivist form of research (von Wright, 1971, p. 38). As regards terminology von Wright calls causal explanations in a positivist perspective simply *explanations* while in the hermeneutic case they are labelled *understandings*. In the first case an explanation relates to sufficient conditions accounting for the causes of certain effects. In the second case understanding results from an assessment of necessary conditions reasonably associated with causes.

Causes precede their effects. The notion of time is a decisive, thought certainly not sufficient criterion for the distinction between causes and effects (von Wright, 1971, p. 41). Von Wright's proposed models of scientific explanation and understanding comply with Bhaskar's critically realistic model. As shown in figure 4, Troye draws a model of different explanation levels based on Bhaskar's critically realistic model (Troye, 1994, p. 132).

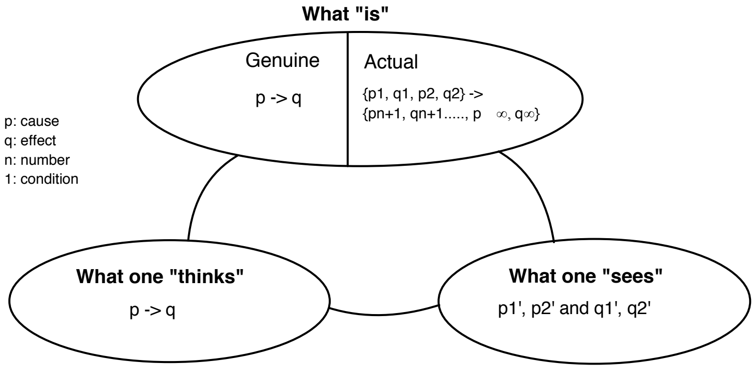


Figure 3 - Troye's explanation model based on Bhaskar's model

Consider a cause in figure 3 to be *p* and an effect to be *q*. One can conceive of their relationship both on the "think" level and in the genuine part of the "is" level. What one perceives is each separate cause *p1*, *p2* etc. together with each matching effect *q1*, *q2* etc. on the "see" level. But one does not experience the relationship between them. But experiments and their theoretical presuppositions and reflection make it possible to gain knowledge about the relationship between p and q presenting themselves in the actual part of the "is" level. On this level each particular state can be observed. One perceives each separate cause *p1* and *p2* with their matching effects *q1* and *q2*. By adding an invisible condition, labelled +1 in figure 4 some presumptions about the effect *qn* from a future cause *pn* can be made. This presumption of future cause and effect is made on the basis of observations of existing cause and effects.

The model in figure 3 is appropriate for explanations belonging to the positivist tradition. Research belonging to the hermeneutic tradition though would be represented inadequately in this model. However, integrating von Wright's model of understanding into Bhaskar's critically realistic model can adequately assess the explanatory power of research from the hermeneutic tradition.

4. RESEARCH CONCERNING SPACE, HUMAN MOVEMENT AND MARKED RATIONALITY

Space Syntax research complies with the positivist tradition in epistemology when only focusing on analysing spatial changes as an effect of physical interventions. While research in the Urban Morphology and place Phenomenology tradition is closely intertwined with human intentions and attached meanings behind the artefacts, the former variety of research seeks to explain how a city is set up as an object, irrespective of human precondition of causation. For this purpose a built environment is conceived as a set of spaces shaping a configurative spatial system. Each physical change in the built environment affects its configurative spatial system.

Research and theory building on built environments becomes more complex when dealing with intentions behind human behaviour. However, Space Syntax researchers have managed to develop a theory on the relationship between spatial configuration, human movement and the location of economic activities.

As Thomas Markus stated in his keynote presentation at the 5th international space syntax symposium in 2005, the theory of the natural movement economic process is acknowledged so far to be one of the best developed theories on built environments. When dealing with human rationality where the intentions are unambiguous, it is possible to predict human behaviour effect caused by spatial changes. Marked rationality and all kinds of rationality dealing with time-efficiency has unambiguous intentions, which makes explanations and theory building possible in line with the positivistic research tradition.

Causal explanation models seem appropriate to assess the explanatory power of Space Syntax. Trivially enough, causes occur before their effects. In the first instance it is thus appropriate to identify the causes of events to be explained. In the main Space Syntax accounts for urban changes as changes in a spatial configurative system.

Human movement in and human occupation of spaces articulate functional aspects of the way spaces are used. Space syntax research searches for causal explanations of changes in a built environment considered as an object and how these changes affect human activities in society in terms of functional changes.

Again, examples referring to the relationship between road building and urban changes will be used. Under the presupposition of Hempel's classical deductive-nomological model, explanations related to marked rationality seem to be more substantial and general than those offered by social rationality:

Explanandum (effect): A newly constructed road changes the flow of human movement and location pattern of shops in a city.

Explanans: The theory of the natural movement economic process: The spatial configuration of a built environment influence human movement and the location pattern of shops.

Explicatum (cause): A newly constructed road changes the configurative system of a city. This change influences the movement routes for travelling from everywhere to everywhere else, and likewise the location pattern of shops.

Hempel's explanation model is a basic achievement of positivist epistemology, but it does not present the linkage between cause and effect in as perspicuous a manner as von Wright's causal explanation models. Space Syntax research seeks to find explanations for the interdependence between physical form and some kinds of human behaviour patterns. As regards von Wright's account of explanation, these preconditions allow for the following instantiation of a general explanation model as regards cause and effect:

Effect (consequences): The spatial configuration of an urban street network is changed.

Cause (reasons): A new movement route has been established.

This causal model is solid as regards general phenomena as well as context dependent cases.

Effect (consequences): The integration value of Bull Ring Square in Birmingham has decreased between 1985 and 2000.

Cause (reasons): A new ring road changed the configuration system of the street network in Birmingham centre. The ring road cut off the street leading to Bull Ring Square from the city centre.

The examples above show how Space Syntax research has explanatory power when dealing only with the physical aspects of the built environment. When adding unambiguous intentions, it works well for both general cases as well as context dependent cases:

Effect (consequences): Shops has disappeared from Bull Ring Square from 1985 to 2000.

Cause (reasons): Birmingham's inner ring road changed the configuration system of the street grid in its centre. This ring road dragged all the integration values away from the town centre's streets.

Effect (consequences): The location pattern of shops has changed.

Cause (reasons): A new ring road contributed to change the dispersal of integration values of the street network.

In general the development of scientific theories aims at an increasing degree of generality. Hence, only general examples are presented in terms of von Wright's explanation models for research related to marked rationality.

4.1 SUFFICIENT AND NECESSARY CONDITIONS

As regards necessary and sufficient conditions in von Wright's explanation models, is a new movement route a necessary or sufficient condition for changing the spatial configuration system in an urban area?

Von Wright: p is a sufficient condition of q.

Space Syntax: A new road link is a sufficient condition for a change in the spatial configuration system.

Von Wright: *p* is a necessary condition of *q*.

Space Syntax: A new road link is a necessary condition for a change in the spatial configuration system.

An essentially positivist explanation model requires sufficient conditions for explaining the relationship between cause and effect. The explanatory power of Space Syntax thus cannot consist in anything more than means to identify the conditions necessary for the occurrence of phenomena of a specified sort. A new road link effectively brings about changes in a given spatial configuration system. Other aspects too can result in configurable spatial changes. However, it is sufficient that only one of them comes into being for bringing about changes in a city's spatial configuration system. In essence Space Syntax sets out conditions sufficient for a change in a built environment. A complex sufficient condition consists in a conjunction of phenomena (von Wright, 1971, p. 39). Again von Wright's schematic description is paralleled with an example from Space Syntax:

Von Wright: Maybe p or r alone is sufficient for that q will occur. But if p and r occur together, q is sure to be there too.

Space Syntax: Maybe a new road link or a road blockage alone is sufficient for that spatial configurable change will occur. But if a new road link and a road blockage occur together, spatial configurable change is sure to be there too.

In a complex necessary condition p and r are logically separated from one another. While a complex sufficient condition consists in a conjunction of a phenomenon, a complex necessary condition presents itself as a disjunction. The subsequent example shows how Space Syntax accounts for complex necessary conditions:

Von Wright: Maybe r does not require the presence of p (unconditionally), nor the presence of q (unconditionally); but r may nevertheless require that at least one of the two, p or q, be present.

Space Syntax: Maybe spatial configurable change does not require the presence of a new road link (unconditionally), nor the presence of a road blockage (unconditionally); but spatial configurable change may nevertheless require that at least one of the two, a new road link or a road blockage, be present.

In a more refined perspective von Wright introduces explanation models as to why something was or became necessary, or, conversely, why something was or became possible. In the "why necessary" type of explanations, sufficient conditions are crucial, and in the "why possible" type,

necessary conditions are crucial (von Wright, 1971, p. 58). Below both explanations models are presented with reference to an application of Space Syntax.

Why something became necessary: A new road link is one of the sufficient conditions for spatial configurable change.

Why something became possible: A new road link is one of the necessary conditions for spatial configurable change.

Here the second example appears to be inadequate. In essence, Space Syntax focuses on the sufficient conditions of changes in urban space.

4.2 ACTIVE AND PASSIVE EXPLANATIONS

Von Wright refines his account of explanation by distinguishing between active and passive explanations. In the second case one search for regularities in a system's development by observations that do not initiate the process under concern. In the first case the initial state of the observed process is produced at will (von Wright, 1971, p. 82).

Space Syntax relies on both active and passive explanations. It is thus possible to observe how movement and occupation occur and compare the results with the spatial configurative analyses as well to block movement routes and observe how a movement pattern will change.

During the last two decades, technological development made possible to test out how people orientate and move through a virtual environment created through computer simulations. With 3D glasses, people are able to move in a lab through these virtually created environments making possible to test how people behave in for example empty or crowded urban areas. In her PhD thesis Spatial Navigation in Immersive Virtual Environment Ruth Conroy carried out experiments concerning the way people choose routes at road junctions in a virtual environment [Conroy Dalton, 2001, p. 47]. Her research illustrates in what way Space Syntax research aims at active explanations.

4.3 COUNTERFACTUALS

Counterfactual considerations are another means to consider the relationship between cause and effect. It is useful to set out what happens if a prediction is not verified.

Space Syntax: If a new road link were not constructed, no change in the spatial configuration system of an urban area would occur.

Conditionals of this form are truly relevant. No spatial change in an urban grid implies no configurational changes. The example shows that Space Syntax research has high degree of predictability.

4.4 EXPLAINING CAUSE AND EFFECT

Space Syntax is designed to set forth research on the built environment as an object purely in terms of cause and effect. It accounts for predictability, where Space Syntax research is set up to predict effects of urban physical spatial changes.

The ascription of meaning or intentions is scarcely relevant in Space Syntax' spatial part. It therefore may be applied independently of any particular human culture. It relates to the built environment as an object as such, irrespective of preconditions such as human intentions and meaning. Hence, and with explicit reference to Bhaskar's critically realist model, explanations in terms of Space Syntax present themselves as shown in figure 4:

The "think" level and the genuine part of the "is" level in figure 4 represent an explanation in terms of cause and effect; e.g. a new road link causing a configurational change of the urban street grid. These two levels represent the changes in non-discursive relationships. Here changes in the integration values of a city's street grid are at issue.

On the "see" level both effects and causes are identified by according representations by maps or models of an entire built environment in a before and after situation. It is possible to perceive each new road link, and the location of functions. An overview of an entire built environment's dispersal of function and street grid is represented on maps or models.

In the actual part of the "is" level one can derive from a set of causes, here several new road links, and their matching effects, thus functional changes, how future new road links will affect the dispersal of functions. The spatial configurative changes are represented as non-discursive relationships, which can explain the relationship between a new road link and changes of space use.

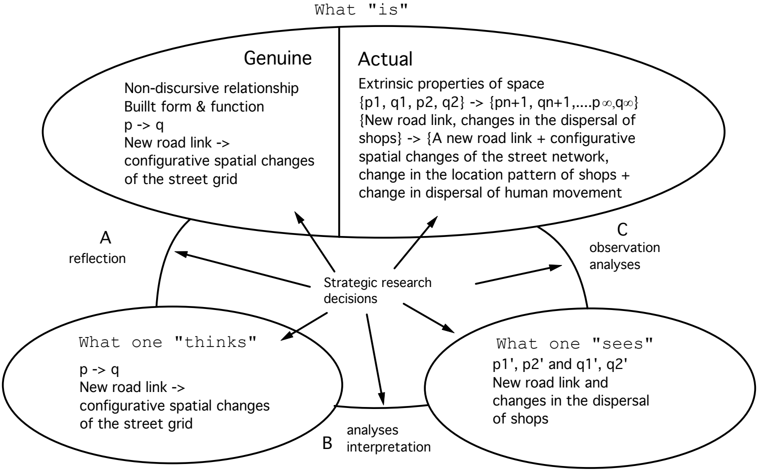


Figure 4 - Space Syntax' explanatory power according to Bhaskar's model

The way in which a comparison between the results of calculations and registrations of changes in space use is visualised in maps or other kinds of diagrams allows perceiving how a new road link changes urban areas. The use of maps and models thus demonstrates how Space Syntax sets out that a new movement route affects urban areas.

Explain the effects of a new road link on urban areas, one registers first the functional changes in a built environment on the "see" level. Moreover, an assumption on that a new road link causes configurational spatial changes in the street grid is made both on the "think" level and in the genuine part of the "is" level. This hypothesis can be strengthened by empirical research recording changes of functions and movement through a street grid and also by calculating the relevant changes in a before and after situation on the "see" level. In the actual part of the "is" level one thus discovers how a new road link affects the functions in an according built environment. In order to identify in all detail a before and after situation of a new road, it is necessary to use maps for seeing how a new road change the dispersal of functions in urban areas.

The explanation represented above pertains only to the built environment as an object. Calculating configurative spatial relationships allows comparing built environments from different cultures. The spatial product created from different cultures can be calculated and compared. Research has shown that Arabic cities have a more segregated structure than

European ones (Hillier, 2001, p. 02.9) and (Karimi, 1998, p. 269-284). However, Space Syntax is not able to make general statements in which various cultures put influence on an urban grid's structure. Research of this kind belongs to a hermeneutic tradition, and has to consider already established urban areas influenced by various cultures. What all cultures have in common are economic activities. Therefore it is possible to make general statements on how activities of this kind react to spatial configurative changes. The theory of the natural movement economic process (Hillier et al 1993) and the theory of the natural urban transformation process (Ye and van Nes, 2014) states that the spatial configuration of the street and road network influence the flow of movement through urban areas, building density, property prices, degree of multi-functionality, and the location pattern of shops.

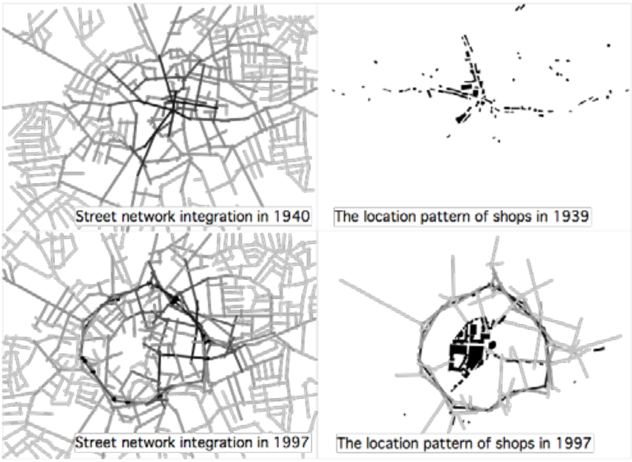


Figure 5 - Example on changes in the pattern of shops as an effect on changes of the street network in Coventry.

Due to these theories' strong causality relation, it is possible to use them to predict future economic related effects on spatial changes. The location of the Millennium Bridge and the regeneration of Trafalgar Square in London affected the flow of movement on various scale levels. These projects are good examples on how changes in a street network structure affected flows of movement. Conversely, the theory of the natural movement economic process makes also possibilities to explain where the shops was located and where the largest flow of movement took place in excavated towns where it is possible to reconstruct its whole street pattern (van Nes 2011). Positivistic explanation models, with a strong relationship between cause and effect makes possible to explain some specific effects on past spatial structures as well as to predict future specific effects on new proposed spatial plans.

5. RESEARCH CONCERNING SPACE AND SOCIAL RATIONALITY

As space syntax research has shown, high spatial integration implies high numbers of people in streets (Hillier et al 1993, 1998), high level of various economic activities (van Nes 2002), high building density and high degree of multi-functionality (Ye and van Nes 2014). What about high spatial segregation and cultural identities related to spatial structures? And what about identifying the spatial structures from archaeological sites or from different cultures?

An elementary scheme will set out how explanations as regards space and social rationality belong to a hermeneutic tradition. Hence, the subsequent argumentation assumes the models of von Wright, Bhaskar and Hempel to be valid, but tries to assess which of these models sets out the form of scientific reasoning essential to urban space and social rationality.

Von Wright's conditional causal explanation models rely on concepts of condition i.e. epistemological notions more basic than quantification and substitution. Research on space and social rationality or historical issues search for explanations in terms of reasons and consequences. But although a cause occurs before an effect, the effects are often easiest to identify. Hence explanations often set out from the effects to discover their causes. Here we will use examples from research on space and anti-social behaviour for revealing this issue.

Effect (consequences): High occurrence of anti-social behaviour takes place in post War social housing neighbourhoods

Cause (reasons): Post War social housing neighbourhoods have a spatially segregated street network

This schematic variety of a causal explanation apparently is too general. Research concerning social rationality is context dependent. In order to explain the occurrence of a particular phenomenon reference to concrete circumstances is mandatory. Therefore an example from a concrete case is used, presented as follows:

Effect (consequences): The Oosterwei area in Gouda is suffering from a high number of loitering youth on the backside of the area's shopping centre.

Cause (reasons): The backside of Oosterwei's shopping centre has a segregated street network with low degree of visibility from adjacent buildings.

As the example illustrates, research concerning space and anti-social behaviour heavily depends on particular examples. Combining von Wright's causal explanation model with Hempel's classical deductive-nomological explanation model results in the following rendering of the Gouda example:

Explanandum: The Oosterwei' area in Gouda is suffering from a high number of loitering youth on the backside of the area's shopping centre (effect).

Explanans: A segregated street network with low degree of inter-visibility from adjacent buildings shape opportunities for anti-social behaviour.

Explicatum: The backside of Oosterwei's shopping centre has a segregated street network with low degree of visibility from adjacent buildings (cause).

The model lacks a certain degree of predictability. When constructing a new neighbourhood with a segregated street network with low degree of inter-visibility from adjacent buildings today, it is difficult to derive from its implementation how its dwellers will behave. It is difficult to propose any kind of regularity or predictability as regards the influence of this particular segregated street structure on other urban areas.

In the first instance, research as regards space and social rationality requires studying the past to acquire an understanding of the intentions, which led to the occurrence of for example anti-social behaviour. Interpretations concerning their meaning, purpose and behaviour are supposed to ensue from their contextualised appearance. In this respect von Wright's concept of conditions is a useful tool to assess what kind of knowledge research on space and social rationality provides.

Von Wright has proposed several logical constructions of statements articulating a proposition's necessary or sufficient conditions. It seems difficult to assess the explanatory power on research concerning space and social rationality with causal explanation models. This kind of research intends to understand the intentions behind a certain type of behaviour, or a culture rather than explaining according causes. Subsequently, in research traditions belonging under the human and social sciences, the aim is to understand the reasons, intentions or motives associated

with these causes. In such cases, explanations as regards forthcoming effects like future city developments or certain kind of behaviour are not given. Accordingly, research on space and social rationality can merely state that certain changes will occur, though not tell in what way.

It seems appropriate to present research on space and social rationality in terms of von Wright's concept of intentionality and his model of teleological explanation. It might seem impossible to invest such a model with a certain degree of predictability for research on space and social rationality. But still a key for analysing its explanatory power could result from an analysis of the meaning of the explanandum (von Wright, 1971, p. 135).

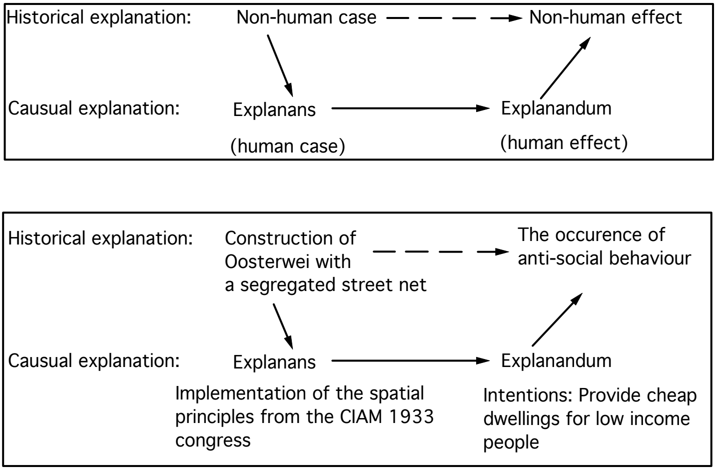


Figure 6 - An example of teleological explanations

When knowing the intentions that brought about segregated street networks, it becomes easier to account for its effects even so it is not possible to predict them on behalf of these intentions. Research on space and social rationality is a historical approach. According to von Wright this involves that its explanatory power should be assessed in terms of *necessary* conditions due to which the effects at issue become *possible*. As implied, historical research such as research on space and social rationality can only examine particular cases.

Time plays a basic role in logical analyses of causal explanation models. Due to its temporal ordering the relationship between cause and effect is asymmetrical (von Wright, 1971, p. 41 and 47).

Research related to cultural, historical and social issues are dependent on already established urban areas. But it is impossible to predict how newly constructed neighbourhoods will function socially.

But in the main, historical explanations are concerned with the question as to how something became possible. They focus on a development's *necessary* conditions (von Wright, 1971, p. 58, 66 and 136). Causal explanations searching for *sufficient* conditions do not pertain to research in history or sociology. Von Wright set up an according model exhibiting the linkage between cause and effect when human will and intentions are involved (von Wright, 1971, p. 137). The explanatory power of research on space and social rationality depends both on human factors

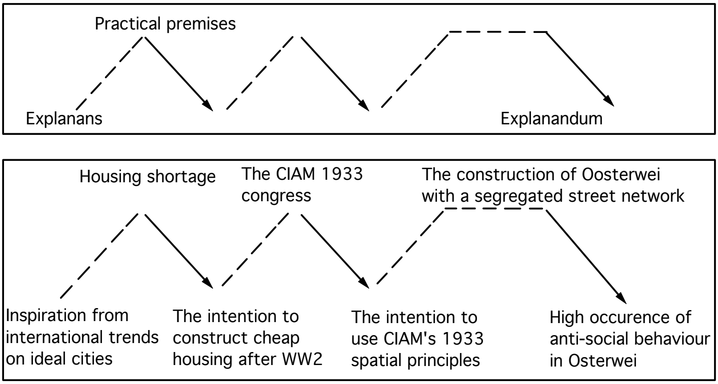


Figure 7 - An instance of quasi-causal historical explanation

like intentions and purposes and on the physical layout of a built environment. The diagram in figure 6 exemplifies how a concrete case from research on space and anti-social behaviour (below) presents itself in von Wright's model (above).

Human intentions or purposes and actual incidents often communicate with one another. Their nested interaction iterates. Von Wright illustrates quasi-causal historical explanations of this sort by the model presented above in figure 7 (von Wright, 1971, p. 143). Here a context dependent issue is used below to illustrate quasi-causal historical explanations. Each phase in an according process of understanding results in a new situation, which allows for new intentions and purposes. The process continues until the explanandum is reached. As this model shows research on space and anti-social behaviour is appropriate when an understanding of meaning and intention beyond the plan of a neighbourhood and its users is at stake.

Valuable understanding requires asking what was necessary for something to become possible (von Wright, 1971, p. 154). Historical incidents allow for further developments as they should transform intentions into effective action and, especially, by introducing new agents with new possibilities to influence their course (von Wright, 1971, p. 155).

5.1 RESEARCH ON SPACE AND SOCIAL RATIONALITY IS DEPENDENT ON NECESSARY CONDITIONS

How does von Wright's explanatory models with necessary and sufficient conditions apply for research on space and social rationality? As research of this kind pertains to context dependent situations, the following disposition parallels these schemata with a particular instance.

Von Wright: *p* is a sufficient condition of *q*.

The Gouda case: The will to implement the ideal city ideals from the CIAM 1933 congress was a sufficient condition for the segregated street structure of the Oosterwei neighbourhood.

Von Wright: *p* is a necessary condition of *q*.

The Gouda case: The will to implement the ideal city ideals from the CIAM 1933 congress was a necessary condition for the segregated street structure of the Oosterwei neighbourhood.

Of these two explanatory schemes the one with necessary conditions is more adequate. For an intention alone does not cause any particular action. However, it is difficult to assess as to whether the intention to implement the ideal city ideals from the CIAM 1933 congress was indeed a necessary condition for constructing the Oosterwei neighbourhood. It could be

that other phenomena were necessary for its implementation. Limited finances at that period equally could have been a necessary condition for that construction. Likewise the coincidence of the mentioned intention with prosperity could have been sufficient for the construction of the types of houses at Oosterwei at issue.

A complex sufficient condition consists of a conjunction of states of affairs (von Wright, 1971, p. 39). Von Wright describes the situation by yet another scheme, instantiated yet again by an example appropriate for research on space and anti-social behaviour:

Von Wright: Maybe *p* or *r* alone is sufficient for that *q* will occur. But if *p* and *r* occur together, *q* is sure to be there too.

The Gouda case: Maybe the intention to implement the ideal city ideals from the CIAM 1933 congress or housing shortages alone is sufficient for the segregated spatial layout in Oosterwei. But if the intention to implement the ideal city ideals from the CIAM 1933 congress and housing shortages occur both, then the construction at issue is sure to be there too.

Complex sufficient conditions thus are conjunctions, and, conversely, complex necessary conditions are disjunctions (von Wright, 1971, p. 39). In the case of sufficient conditions von Wright presents the relevant asymmetry by the following scheme, again instantiated by an example from research on space and anti-social behaviour:

Von Wright: If *p* or *r* is sufficient for that *q* will occur, then *p* by itself is sufficient and so is *r* by itself.

The Gouda case: If the intention to implement the ideal city ideals from the CIAM 1933 congress or housing shortages alone is sufficient for the segregated spatial layout in Oosterwei, then the intentions to implement the ideal city ideals from the CIAM 1933 congress is itself sufficient.

Again, the examples indicate that in a hermeneutic context the assessment of sufficient conditions does not have explanatory power. Research on space and social rationality is supposed to reconstruct the past and therefore has to search for intentions and purposes as conditions necessary for the development of a certain kind of urban area. In what way the spatial layout of a neighbourhood influence the social behaviour of its users is too complex to be derived and depends on extra intentional factors. Neither can one predict as to whether a certain behaviour will occur, nor can one assess in what way it will take place. The explanatory power of research on space and social rationality tradition can consist only in an identification of the intentions at least necessary for a given course of events.

5.2 PASSIVE EXPLANATIONS

Apparently research on space and social rationality does not provide active explanations for it cannot initiate what it is supposed to account for, i.e. the impact on human behaviour. Developments of this kind are being observed without any chance to interrupt or influence them. And it seems equally impossible to simulate them in computer models for they cannot account for the aesthetical values and intentions that influence the making of plans and the implementation process of these neighbourhoods. Finally, it simply is impracticable to design experiments concerning historical, i.e. past events. Active explanation models are thus not part of research on space and social rationality.

5.3 COUNTERFACTUALS

Yet another way of assessing a causal relationship consists in the use of counterfactuals. In this case a statement's explanatory power is specified by figuring out what would have happened if this proposed statement had not come about.

The Gouda case: If Oosterwei centre did not had a segregated street structure, the group of loitering youngsters would not be present on its streets.

A statement of this kind has little explanatory value. For other courses of events could have occurred that would contributed to loithering youngsters in Oosterwei's centre. When taking

human intentions and purposes into account, the counterfactual statement is as follows:

The Gouda case: If there had not been a will to implement the ideas for an ideal city from the CIAM 1933 congress in the planning and implementation for Oosterwei, this neighbourhood would not get a segregated street network.

Here the statement's explanatory power is increased. A counterfactual condition is set but in terms of human intentions being necessary for a certain development.

5.4 UNDERSTANDING THE INTENTIONS OF A CAUSE

As all these examples of explanations show research on space and social rationality does not lead to general statements on built environments due to its context dependency. For grasping the sense of a neighbourhood's spatial layout depends on understanding the cultural preconditions of their production.

A systematic analysis and interpretation of built form and meaning requires a hermeneutic methodology. For a society's ideologies, symbolic values, and attitudes constantly change and their articulation varies from one settlement, to another. An interpretation of how activities in a society shape urban space accordingly requires developing an understanding of both the built environment itself and its position in its comprehensive context. Interpretation processes that account for such interactions between parts and wholes of physical objects and their meanings are often called hermeneutic circles (Føllesdal et al., 1996, p. 105). As regards research on space and social rationality, this form of investigation consists at least in the following: identification of various spatial layouts, understanding them first in terms of the intentions that necessarily conditioned their existence, destruction or alteration and then in terms of the sense they acquired, finally assessing their relationships with a built environment in its entirety. Any progress in one of these phases leads to a refined or revised account of their meaningful existence in subsequent phases of the mention kinds.

In the first instance an according application of this basis method consists in proposing hypotheses about a built environment's structure. In its next phase it requires to search for an understanding of the historical contexts of the built environment's type of spatial layout. These can consist in political, economical, and societal circumstances as well as cultural preferences

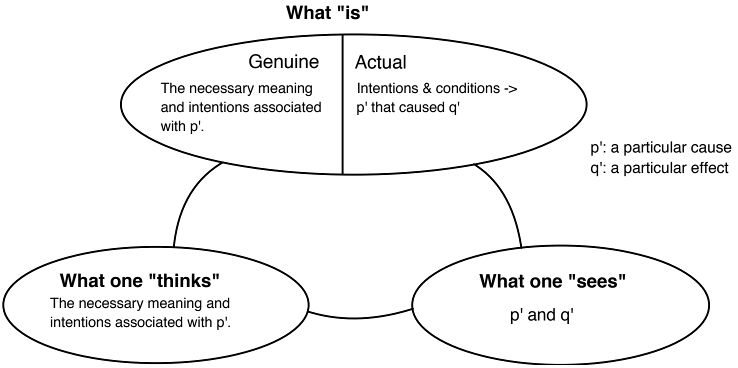


Figure 8 - Troye's revised explanation model

that were influential at that time the relevant spatial layout came into being.

As shown in figure 8 a revised presentation of Troye's model in figure 3 should thus reckon with von Wright's explanation models: one is supposed to search for an understanding of the meaning of a specific phenomenon *p* that caused *q*. It is impossible to say anything about how *p* caused *q*, even though it is possible to register *q*.

The sketch obviously pertains to research on space and social rationality. According to figure 8, a specific cause and effect of a specific phenomena can be identified on the "see" level. The cause is labelled *p'* and the effect is labelled *q'*. On the "think" level one is searching for an understanding of meanings and intentions members of a society had and that caused *p'*. This level represents the necessary conditions of the cause *p'*. The genuine part of the "is" level represents the invisible necessary conditions for the meaning and intentions for that the cause *p'* came into being. The way the particular cause *p'* and its effect *q'*, present themselves represents the actual part on the "is" level. The visible documentation of the identified necessary meanings, intentions and conditions that produced *p'* are also represented here.

Due to the context dependence of explanations belonging to a hermeneutic tradition, each *p'* with its according meanings and intentions has to be treated separately. The model in figure 8 cannot be used for gaining general statements on the relationship between meaning and intentions that caused *p'*.

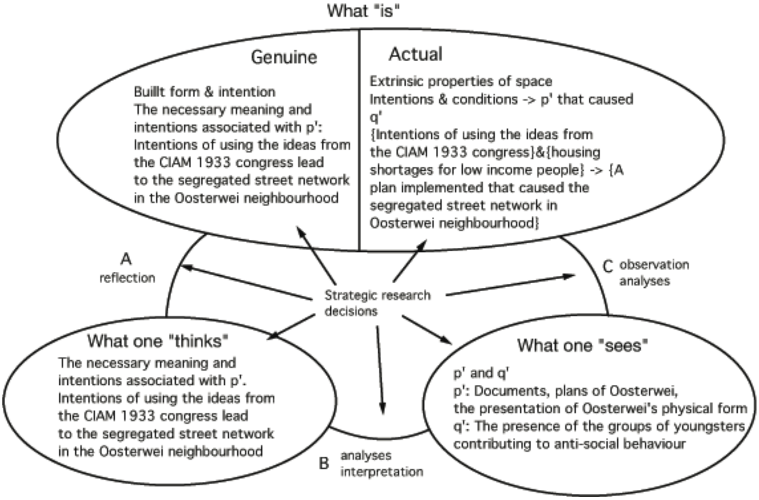


Figure 9: The explanatory power of research on space and anti-social behaviour through the use of Troye and Bhaskar's model.

Research according to this model has to consider a particular culture and its influence on the built environment. Under these circumstances, cf. figure 9, it seems adequate to use Bhaskar's critically realist model to account for research on space and social rationality.

Hence, the following can be stated: Society and its impact on the shaping and forming of the built environment needs a hermeneutic approach where the purpose is to gain *understandings*

on how activities in society influence urban form. Research of this kind is context dependent and therefore it is difficult to make general theories on the relationship society's influence on its spatial outcome. Conversely, how a built environment's spatial layout affect human behaviour requires both a positivistic as well as a hermeneutic approach. On research as regards space and marked rationality a positivistic approach is possible to gain explanations on how a built environment's spatial layout affect activities in society as regards movement and the location of economic related activities. The theory of the natural movement economic process and the theory of the natural urban transformation are examples on general theories able to *predict* effects of the causes. However, research on space and social rationality is context dependent.

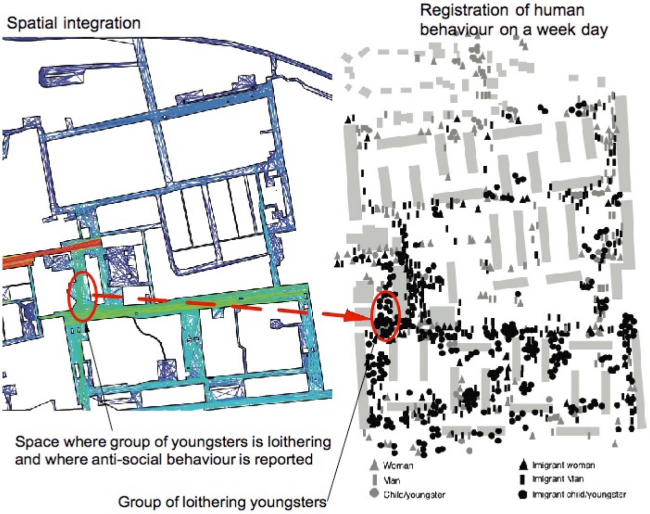


Figure 10 - The Oosterwei case in Gouda

Therefore, there exist no general theories on for example the relationship space and anti-social behaviour, or for example a theory on "space and crime".

6. CHALLENGES FOR THEROY BUILDING IN SPACE SYNTAX

What are then the challenges for theory building on built environments? Bill Hillier's main question proposed at the 10sss keynote paper: what are cities for? His answer was to create contact. For urban design and urban renewal issues, there is a need for a theory of the spatial conditions for creating contact. Here the theory of the natural movement economic process for *explaining* the location of economic activities and to generate many people in streets seems to be appropriate. One step further, a draft of a theory on the natural urban transformation process is already present. The aim is to explain how a natural urban transformation processes occur. So far, this theory's empirical support is based on big data on a couple of new and old towns in the Netherlands and China (Ye and van Nes 2014). Since the street network configuration is steering degree of building density and degree of multi-functionality, a causual explanation model is here used. The effects are that high building density and high degree of function

mixture is dependent on the spatial structure of the street network. Therefore, a change in the spatial structure of the street network is a sufficient condition for influencing building density and degree of multi-functionality in a settlement.

In general, research concerning human intentions that are unambiguous makes stronger predictability on the socio-economic effects of spatial interventions than research dealing with complex cognitive as well as socio-cultural factors that are heavily context dependent.

Most research on built environment has so far a strong hermeneutic approach. It accounts for place phenomenological approaches as well as for various morphological approaches. In the field of Space Syntax, research concerning space and crime/anti-social behaviour, historical and archaeological research, research concerning various social anthropological or cultural traditions' impact on urban space, and research dealing with spiritual/religious activities in relation to space, requires also a hermeneutic approach. The degree of predictability is not an issue here, and therefore there exist no explanation models or theories on for example the relationship between urban space and crime/anti-social behaviour. Understandings on these issues require investing already established areas.

Therefore, it is difficult to predict how for example new areas can generate safe urban areas or the opposite. As Juval Portugali writes, human beings are cognitive beings, where they can travel back and forward in time as regards their memory. That makes urban research a complex issue. However, the physical outcome – the built environment – is the media of interaction (Portugali 2013, p. 3). Therefore, theory building on how built environments works and set the framework for socio-economic life for human beings requires to be clear on the distinction between the physical form and the meaning, behaviour, memories etc attached to it.

What has Space syntax contributed to so far in theory building on built environments? In line with the positivistic tradition, it is obvious that Hillier's theories on spatial laws or combinatorics (Hillier 1996, chapter 8) have a strong link between cause and effect:

The principle of centrality: A central placed object increases the topological depth more than one placed at the edge.

The principle of extension: Partitioning a longer line increases the topological depth that a short one.

The principle of contiguity: Contiguous blocks increase topological depth more than separate ones.

The principle of compactness: Straight lines increase topological depth more than "curled" lines.

These principles or explanations focus only on the built environment as an object. Intentions and human rationalities are not taken into account here. Likewise, a first draft of a theory on the relationship between macro and micro spatial layouts of cities is proposed. It states that the higher number of direction changes a street has from a city's main routes, the more entrances from buildings are turned away from streets (van Nes & López 2010). At present, more evidence is needed to strengthen this theory.

Space syntax has been able to build some general theories on urban space and human behaviour with unambiguous intentions. The application of the theory of the natural movement economic process in research worldwide has shown that the location of economic activities and the flow of human movement are dependent on the spatial structure of the street network. At present, a first draft on a theory of the natural urban transformation process is on the table. Some evidence is present from Dutch and Chinese cases, but more empirical support is needed (Ye and van Nes 2014). The results so far show that building density and degree of multi-functionality heavily depend on the spatial structure of the street network.

What has space syntax contributed so far to general understandings on the relationship between society and its impact on urban space, or how spatial layouts affect activities in society? On the relationship between society and space, the following has been done:

The socio-anthropological approach: Contributions on understandings on how past cultures shape their spatial structure on built environments (Hillier and Hanson 1984) (Hillier 2016)

The historical approach: Understandings on the occurrence of societal, technical and economic changes through history and their influences on the spatial structure of built environments (Hanson 1998).

The archaeological approach: Connecting the location of artefacts and interpretation of spatial functions together with an interpretation of the spatial analyses of excavated towns (Stöger 2009, Crane 2009, van Nes 2011)

The urban planning approach: Political decisions, rules, policy and planning and building laws (van Nes 2007 and 2009)

The sociological approach: On the relationship between space and society, the following has been done (with a couple of examples of references):

- Understandings on the relationship between space and crime/anti-social behaviour (van Nes & López 2010, Shu 2002, Sahbaz & Hillier 2005, Greene 2003)
- Understandings on the relationship between space and cultures (Vaughan & Penn 2006, Aghabeick & van Nes 2015)
- Understandings on the relationship between space and behaviour (Rooij & van Nes 2015, Rueb & van Nes 2009,
- Etnicy, gender, sociological issues and the use/behaviour of the city (Vaughan & Penn 2006, Aghabeick & van Nes 2015, Nguyen & van Nes 2014), Powerty issues (Holanda 2012, Greene 2003, Mohammed & van Nes 2015)
- Understandings on the relationship between space and cognition (Hillier & Iida 2005, Conroy Dalton 2001)

To conclude, building theories on built environments based on space syntax research has both explanatory power components from the social and human sciences as well from the natural sciences. To illustrate this, Hillier's attempt to built a theory or understandings on the generic function of cities (Hillier 1996, 2016) has a positivistic as well as a hermeneutic component. Hillier's concept of the "foreground network" explains the location of micro economic activities, whereas his concept of "the background network" provides understandings on the relationship between culture and space.

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