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3D-INFORMED CONVEX SPACES

The Automated Generation of Convex Representation for Open Public Space Analysis

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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

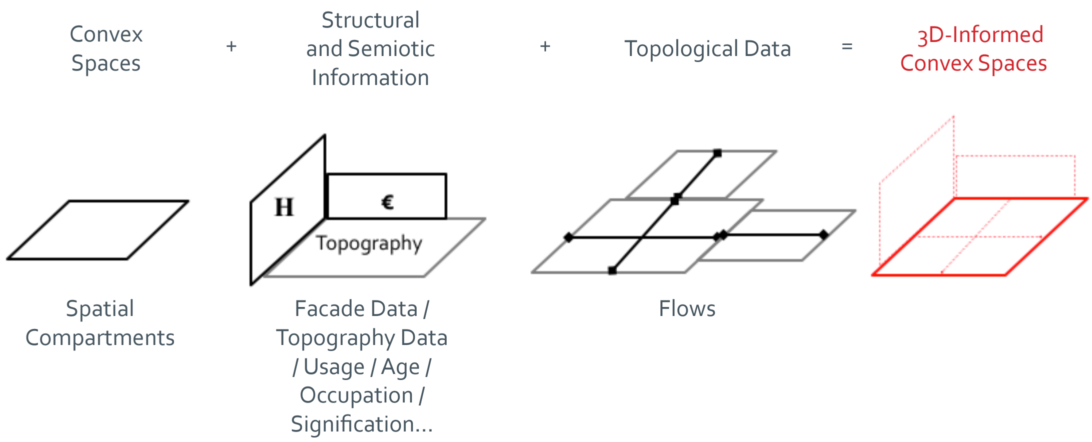
2.1 USABILITY OF CONVEX SPACES REPRESENTATION IN URBAN STUDIES

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

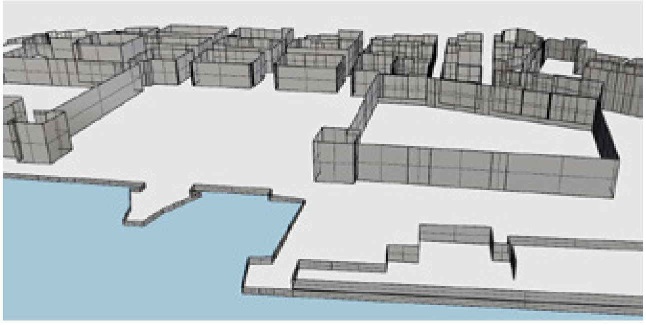
Volumetric limits such as buildings and water surfaces are approachable only from outside thus define certain unapproachable area within urban voids.

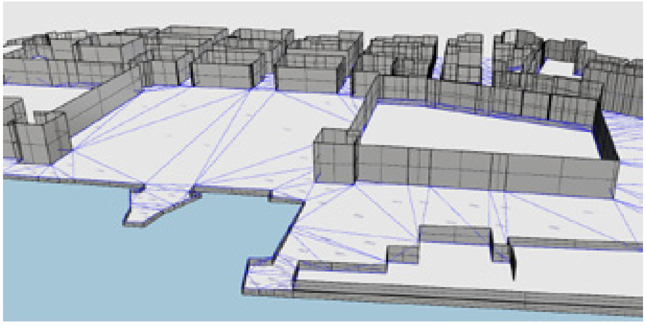
Implicit limits

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

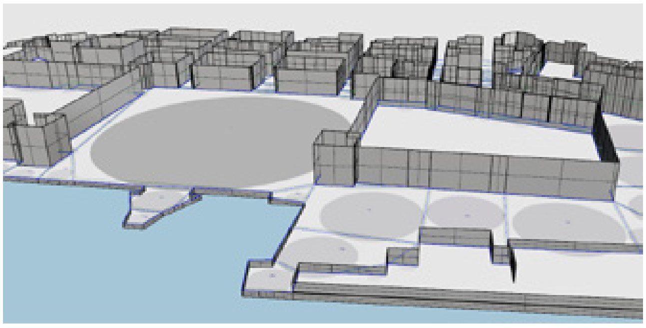

3D-informed Convex Spaces

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]

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.

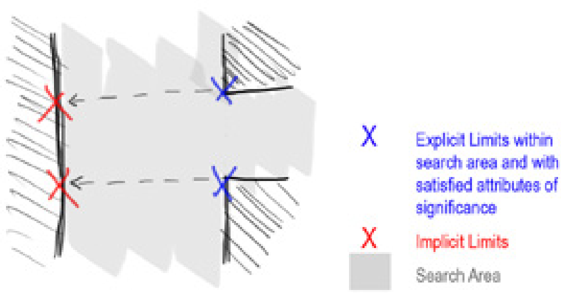


Figure 3 - A sketch that explains construction of Implicit Limits

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.

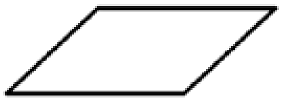
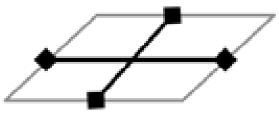
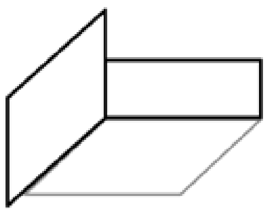
3D-informed Convex Space	Short Name	Name	Property
	CS_Id	Convex Space	ID attributed to Convex Space
	CS_Area	ID	CS Area calculated from the area of all belonging triangles
Convex Spaces 	**CS_Per**	Convex Space	CS Perimeter calculated as length of 3D circumferential polyline
	CS_Circ_Diam	Area	Diameter 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
	Fac_ID	Facade IDs	ID attributed to Facades
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.

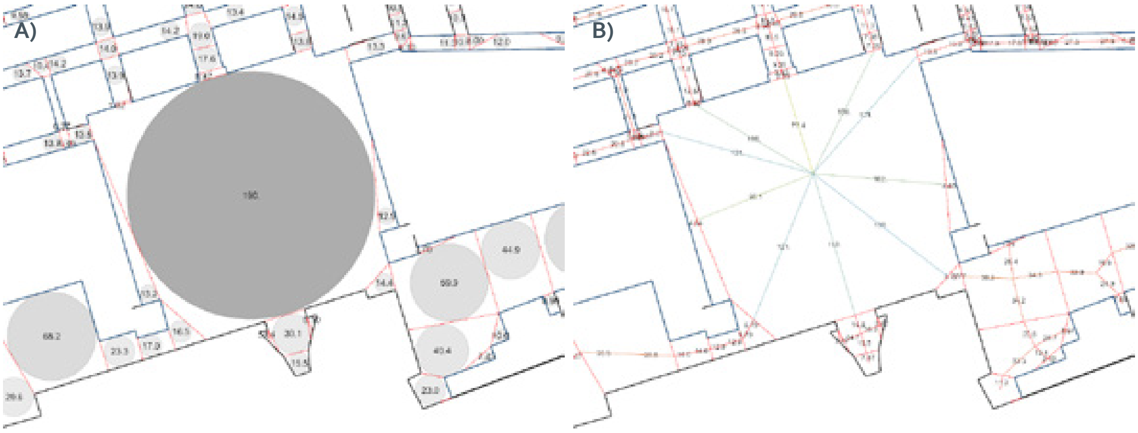


Figure 4 - 3D-informed convex map properties – A) Maximum inscribed circle, B) Flows length

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.

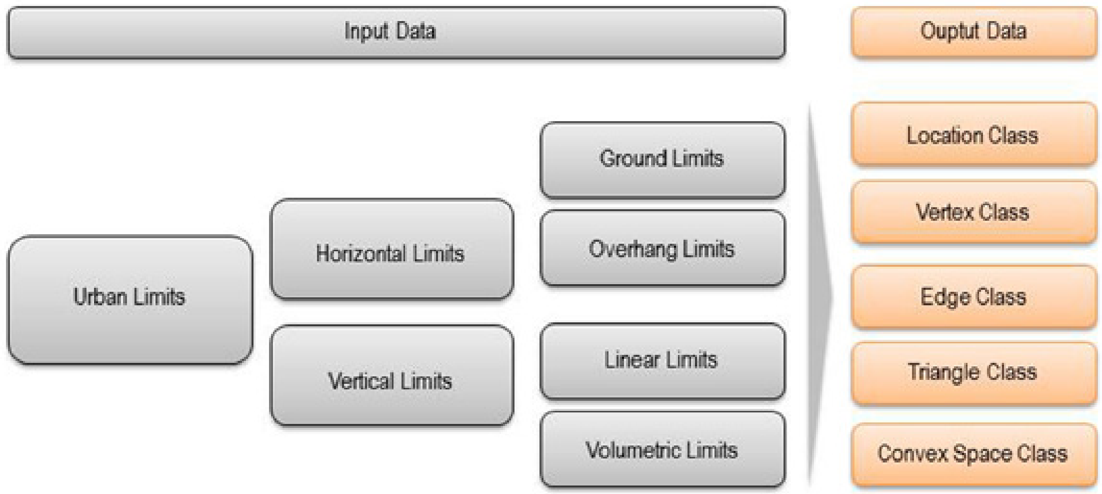


Figure 5 - 3D-informed convex spaces as part of broader representational model

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.

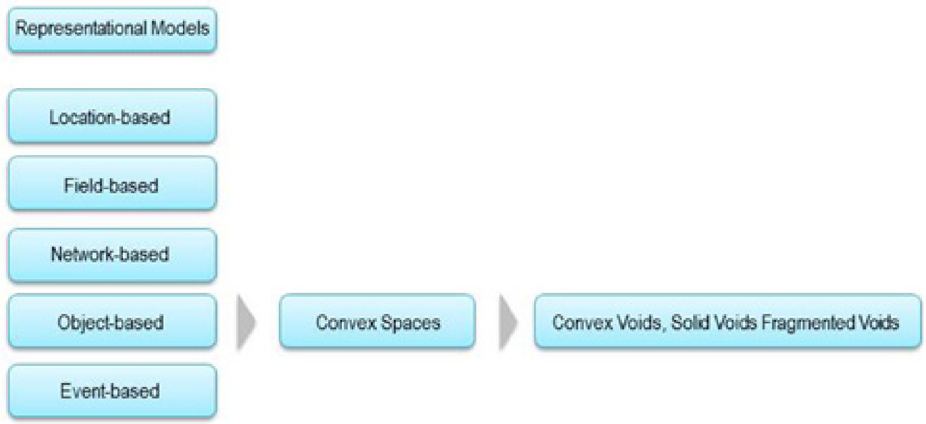


Figure 6 - Possibilities for further representational models

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).

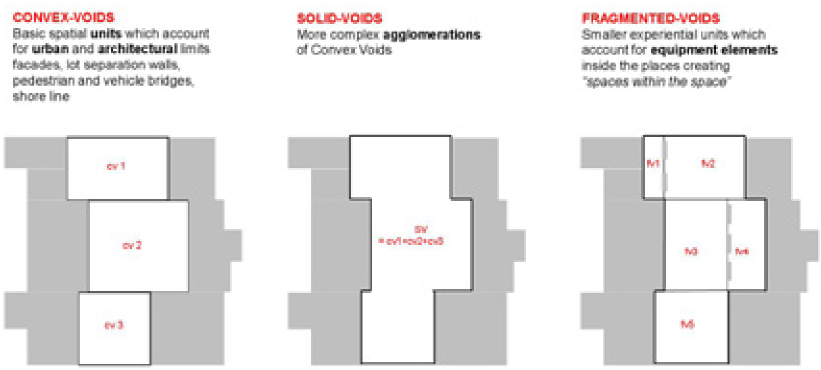


Figure 7 - Possibilities for further representational models – CV, SV, FV

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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