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Parametric Analysis of Relation Between Tall Buildings and Adjacent Public Spaces in Aspect of Urban Parameters and Perception

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ABSTRACT

City is a constantly dynamic viable environment composed of its urban structure, space in-between and its users, inhabitants. The urban environment is a type of "positive - negative" game between voids and volumes with implication of users determining all the dynamics occurring in urban development. The volumes are apparent in form of buildings, structures, superstructures and natural elements, the voids are invisible world geometrically defined by surrounding volumes - open spaces in-between. The specific type of urban volume are tall buildings apparent in most contemporary European cities. The paper uses case of 3 different cities of different scale and characteristics. The main focus is on authors' proposal for process of parametric representation and analysis of urban environment, particularly public spaces (3D voids), using 3D city models. The article presents process from definition of such 3D voids (public spaces) in 3D cityGML models, through parameterization, finally to proposal of multi-level approach to analysis of urban parameters and perception. Analytic part refers to selected geometric aspects of the voids between buildings. The presented sample application contains: a) proposal for generating 3D geometry of public spaces (in areas around tall buildings - using 3D cityGML models, b) sample of analytic interpretation of 3D voids generated in virtual city models with selected urban parameters. Finally, the paper delivers overview of presented proposal for specific parametric computer analysis of geometry of space between buildings – here, specific areas close to tall buildings. The article is a part of the research project 2TaLL: Application of 3D Virtual City Models in Urban Analyses of Tall Buildings under Polish-Norway Grants scheme.

Keywords: *public spaces, urban parameters, tall buildings, 3D city models, urban analysis*
Theme: *methodologies, urban morphologies*

1. Introduction

During the last decades of development in field of computer techniques, urban analysis supported by computer tools becomes very important field of scientific and practical exploration. The process is driven by development of software applications and mathematical methods for spatial data interpretation (Páez and Scott, 2005). The core spatial data for computer analysis is also under intensive development. One of such carries of data, which have been recently widely popularized and developed are virtual city models. We can observe a multiple use of 3D models in open-access purposes (Google Earth etc.), as well as in professional systems for spatial analyses. GIS systems are the most intensively developing environment for advanced urban analysis. However, the still actual challenge for virtual city models remain standardization of data. The very perspective data format in aspect of usability for analytic purposes seems to be cityGML – part of general GML (Geography Markup Language) encoding standard by Open Geospatial Consortium (Gröger, Kolbe, Nagel, Häfele, 2012). Characteristics and potential of cityGML data in combination with CAD, GIS enable very wide range of urban analyses. One of the fields are open areas in urban structures – public spaces. The general life between buildings (Gehl, 2003) in human behaviour dimension is most important for understanding the phenomena in general, however it appears within certain geometry, which is a point of interest in here.

In the very general glance, space between buildings seems to be challenge for measurable and parametric interpretation. The space is overlapping worlds of physical objects, human behaviours and invisible geometry. Although appearance and geometry of buildings is clearly visible, the geometry of public spaces is quiet unnoticeable. This particular aspect has led to the idea of using virtual space of 3D city models for geometrical description of such spaces in-between and further on, parametric interpretation and urban analysis of the phenomena.

2. General approach

General intention for the presented process of parametric interpretation of 3D geometry representing space between buildings in virtual city models is attempt to complement analyses 'towards measuring existing and proposed spatial layouts' (Space Syntax) and 3D analyses of buildings and general built-up areas (City Form Lab) by introducing missing geometry of 3D voids between buildings in virtual city models. The notion of 3D void (empty, open space between buildings) and detailed computer operations to generate the geometry, as well as specifications of cityGML data format, was described in previous papers (Zwoliński, 2013, 2014). Crucial factor is understanding role of 'positive – negative' relation between built-up structure and space between – the proposed approach introduces missing geometry between buildings marked out by surrounding objects (terrain, buildings etc.). The figure below presents general vision of geometry of the 3D voids generated in virtual city model (blue triangular geometry between buildings).

The second important aspect of undertaken approach is using 3D city models not only as multiplicity of virtual anonymous geometries, but as three-dimensional structure with recognized components. This is provided by cityGML standard with its own semantics (definition of such elements as walls, roofs, floors, TICs, as well as component geometries of points, lines, faces and solids) (Kolbe, 2009). The above premises led to proposal of definition of the 3D geometry between buildings using imported cityGML data, combined with CAD / GIS environments to perform specific types of urban analyses on cityscape in aspect of morphology of public spaces.

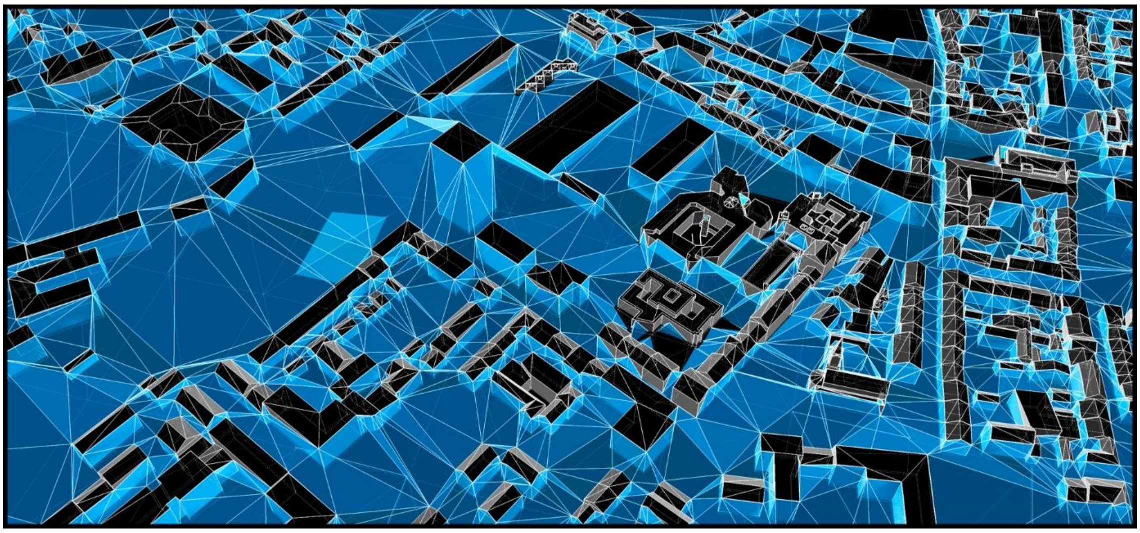

Figure 1 Voids (blue) vs. volumes (black) concept of urban environment – basis for parameterization and urban analysis of public spaces using virtual city models. (by author)

3. Definition of 3D voids

The entire process of generating 3D voids bases on positive-negative geometrical interaction between volume of built-up urban environment and the space in-between. The general assumption behind is, that all the open spaces between buildings can be defined and observed as three-dimensional geometry - negative in relation to 3D objects representing buildings and structures in virtual city models. Further analytic actions on urban 'negative' depend on definition and adding to virtual city model a new 3D geometry representing space limited by built-up structures. Despite different existing standards of digital 3D models, the specific standard of cityGML virtual city models was chosen for application of the presented analytic approach. The cityGML standard is special, because of its semantics (Kolbe, Gröger, Plümer, 2005). All the geometry is recognizable as different classes of objects (terrain surfaces, ground surfaces, wall surfaces, roof surfaces etc.) and can be represented as different geometric components (points, lines, faces, solids) in five different Levels of Detail (LOD0 to LOD4). Additionally such models can be supported by individual database of attributes enabling recognition and comparison of different selected elements. These are crucial premises for introducing and application process of automated definition of three-dimensional geometry of space between buildings based on cityGML standard.

The initial point of the procedure is **reading and importing cityGML model**. The data import tools for GML, XML data formats are already delivered by different software applications (FME, ArcGIS interoperability tools, Sketchup GML reader etc.). The main assumption for the presented process was converting cityGML into readable data for CAD or GIS environment, as well as getting proper structure of 3D model with identification of component geometries (mainly structure of layers with *ground surfaces, wall surfaces and roof surfaces*). In this particular case, for importing GML into AutoCAD and Quantum GIS, some additional procedures were written (AutoLISP for AutoCAD, Python for GIS). It is important to mention at the initial stage that, the LOD (Level of Detail) is crucial for further accuracy of created geometry of 3D voids – LOD1 does not provide data on roof structures, it comes with LOD2. However, both of the levels are usable for the process.

The background and inspiration for next stage called **cityGML explode to point cloud** was partly characteristics of LiDAR data (Kada, McKinley, 2009) using point clouds from 3D scanning, and partly multi-level geometry components (points, lines, faces or solids) provided during cityGML data conversion. The steps for exploding imported cityGML model were firstly to explode geometries from 3D face / 3D polyline level into set of lines divided in groups of vertical, horizontal and angled lines. Afterwards, automated detection of start – end points of lines was applied (in CAD and GIS environments for data comparability). The figure below shows on the left-middle side cityGML model of Loerrach (Germany) exploded to XYZ point cloud after removing other geometries. The example shows full range of automatically detected points before process of elimination of multiple X,Y axis points with different Z coordinate. The applied procedure removed lower Z coordinate multiple points to separate layer excluded from further actions. The remaining point cloud of top Z points (similar to DSM *Digital Surface Model* or DEM *Digital Elevation Model)* (Li, Zhu, Gold, 2005), was used for further stage of presented process.

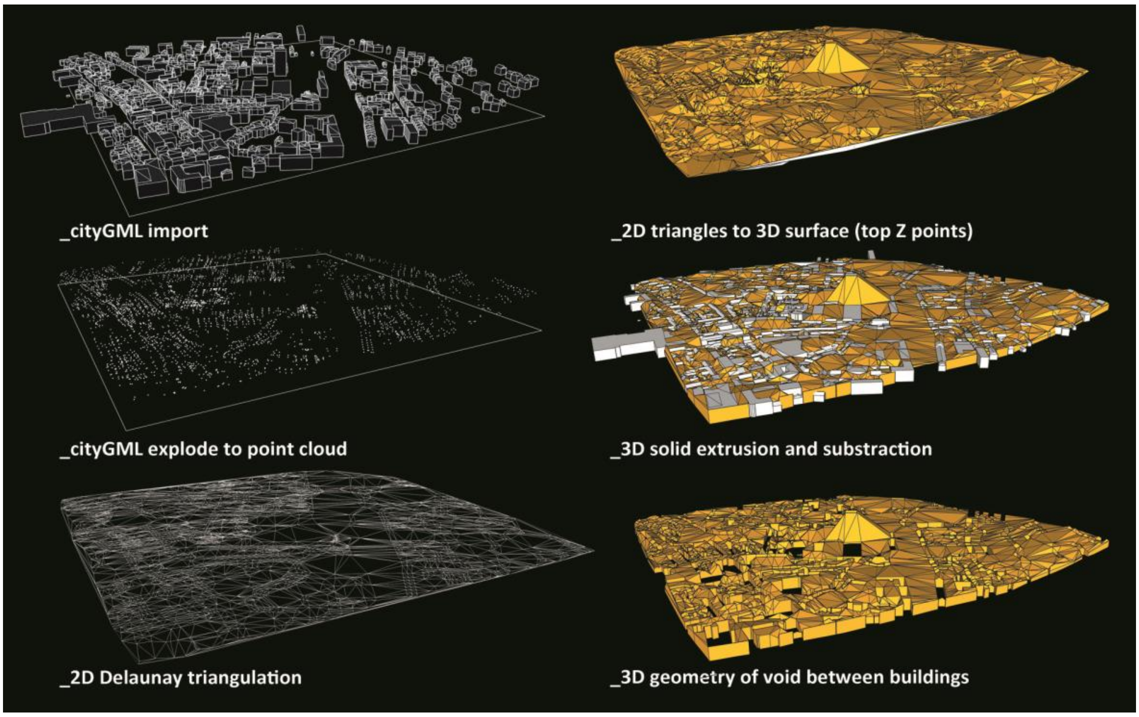

Figure 2 Process of definition of 3D voids geometry in virtual city model of Loerrach (Germany) in six following stages. (by author)

After the detection of so called point cloud from geometry delivered by cityGML standard, the **2D Delaunay triangulation** (de Berg, Kowaluk, 2007) adopted from field of geometry was performed. The generated point cloud was transferred in .TXT file format (with all the points as XYZ coordinates) to Quantum GIS application. The 2D Delaunay triangulation procedure was applied to connect all the points and generate triangular flat grid – which afterwards, was transferred back to CAD application. The same stage was performed also using only GIS environment to compare data accuracy – the comparison indicates advantage of procedures in Quantum GIS (the difference is seen on Figures 5 and 6).

Converting **2D triangles to 3D surface (top Z points)** reused the point cloud (highest Z coordinate points) to align flat result of triangulation to the highest detected points on geometry delimiting space between buildings. The result was 3D triangular surface attached to the top of virtual city model objects. The surface also defined a type of ceiling over urban space. From this stage, all the actions within described process were performed in CAD applications (AutoCAD, Sketchup Pro).

The last procedure performed on 3D city model consists of two basic operations. The first one was **extruding 3D triangular mesh into 3D solid geometry** – in this stage obviously overlapping original 3D buildings and structures. Afterwards, the second operation separated those two types of ‘positive’ and ‘negative’ geometry by **Boolean subtraction** tool. The middle-right side of Figure 2 presents composition of those two types of 3D geometry within virtual city model of Loerrach. The same process was performed on virtual city models of Delft and Rotterdam. Finally, the result of presented process was complex **3D geometry of void between buildings** remaining after removing the “positive” geometry of built-up structure of the city. This type of 3D void detected using core cityGML data and processed in CAD application is an autonomous 3D geometry representing public spaces within the specific areas of selected cities.

4. Introducing sample areas

The presented sample application of urban analysis of public spaces using concept of 3D voids in virtual city model was performed on approx. 1x1 km areas of 3 European cities. These are areas from Delft (Netherlands), Loerrach (Germany) and Rotterdam (Netherlands). There were several urban, typological and technical premises for selecting these locations.

In sense of urban morphology and impact of tall buildings, the cities have different characteristics. Delft is a small Dutch city on regular gird, with mostly uniform scale and height of buildings, located on flat landscape, with two tall building historical dominants of Nieuwe Kerk (New Church) and Oude Kerk (Old Church) located in the very city centre. The selected 1 km^2 area surrounds the tower of Nieuwe Kerk. The building density and regular urban blocks clearly enclose public spaces within streets and regularly defined squares. The city of Loerrach in southern Germany is also small city, but located on beautiful hilly landscape, with small town type of buildings, with single dominant of Loerrach Town Hall tall building located in the city centre nearby main railway station (Figure 3 – in the middle). Presented in the paper analyses are performed on the 1x1 km area in this part of the city. Due to different landscape conditions, the structure of public spaces is much more differentiated, in sense of scale and geometry, than in Delft. Last selected location is city of Rotterdam, completely different urban scale and impact of tall buildings. The sample area was defined in the very centre of big Dutch city, located on flat landscape, but very differentiated cityscape by many tall buildings grouped in the area (called Stadsdriehoek). This system of public spaces is the most complex one – presented sample analysis touches upon only general geometry between buildings, in fact localization in Rotterdam needs much more detailed analysis focused only on this city.

The data input and technical premises for selection of these 3 sites were mainly related to quality and type of cityGML data used. The core cityGML datasets for Delft, Loerrach and Rotterdam were open source data, but with different characteristics and content. CityGML model of Delft was the simplest one, in LOD1 and without terrain surface (it was basically not needed in this case because of Dutch flat landscape). City of Loerrach has the most advanced and accurate cityGML dataset, including LOD2 data and terrain model. The city of Rotterdam is has also very good quality of cityGML data, including LOD2 data with textures – terrain model was also not used in this case.

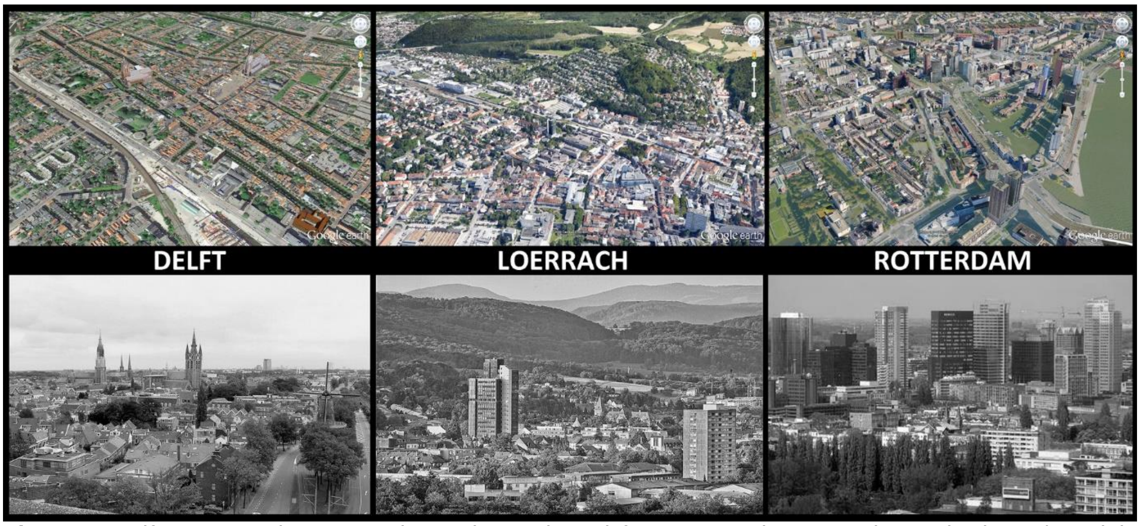

Figure 3 Delft – Loerrach – Rotterdam. Sites selected for case study – Google Earth views / models above, views of the city landscape below. (figure by author, source: Google Earth / Panoramio)

5. Parametric interpretation

Introduction of the entire process of definition of 3D voids representing public spaces between buildings in form of three-dimensional geometry was intended to show overview of possibilities and indicate types of urban analyses possible to perform using such object. Sample of 3D voids were detected and defined in virtual models of all 3 cities, on areas about 1x1 km (in case of Rotterdam it was double – 1x2 km). The aim was to indicate and observe urban parameters of city landscape in areas around tall buildings, focusing on parameters of space between buildings. The paper presents only sample interpretation of selected parameters and indicates potential of using 3D city models in urban analyses regarding geometry of public spaces. After performing presented process of definition, resultant 3D geometries of public spaces were put under estimated autonomous 5 types of parametric interpretation. These types are: type 1 – city spectral profile (CSP), type 2 – typology by slope (TBS), type 3 – typology by length (TBL), type 4 – typology by area (TBA) and type 5 – perception issues. The names are proposed with abbreviations to simplify further explanations.

5.1. Type 1 – City Spectral Profile

This type of parametric interpretation bases on spectral approach using series of sections / profiles through geometry of 3D voids. Observation of number of subsequent sections was intended to recognize type and changes in public spaces profile in different types of cityscape where tall buildings are located. The profiles were detected by automatic 11 sections by each 10 meters of model depth (in case of Rotterdam 20m) in direction perpendicular to location of tall buildings. Setting all sections for each area in one matrix allowed recognition of some regularities in typology of profiles. Lighter area marked on Figure 5 on samples from Delft and Loerrach shows similar behaviour of profile in case of single dominant tall building. The case of Rotterdam show more irregular and extended field because of concentration of tall buildings in limited area. The table below shows measured values for each 3D void (number of sections / distance between sections / angle of boundary nearby tall buildings).

Table 1 Sample measurement from spectral profiles for each selected site. (by author)

3D void	No. of sections	Distance [m]	Angle at tall buildings [°]
Delft	11	10	56-68
Loerrach	11	10	36-60
Rotterdam	11	20	41-56

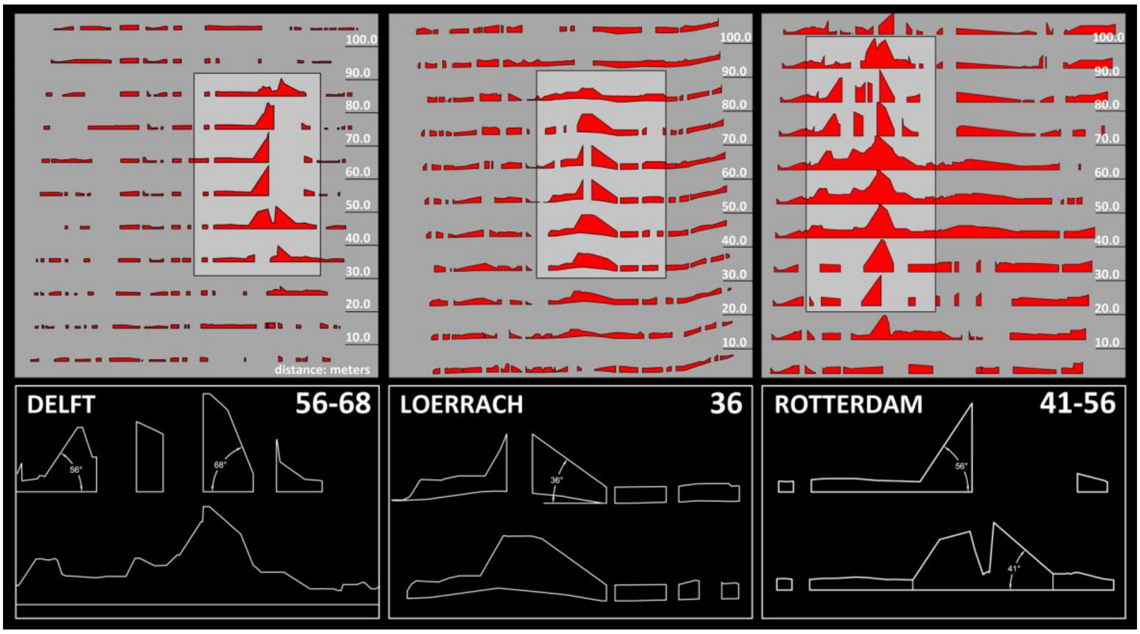

Figure 4 City Spectral Profiles generated for 3 selected areas in Delft, Loerrach, Rotterdam. Appearance of public spaces around tall buildings is marked by lighter grey, measured angle below. (by author)

The interesting parameter supporting interpretation is the angle of boundary of area directly around tall building / group of buildings. The angle stands not only for direct height of the building but also ratio between height and size of adjacent open space. Important remark is, that the scale of profiles (height / extend) is true and undistorted (figure above shows extend of 1 km for each area). It also depends on typology of buildings – the lower values (41-56°) for Rotterdam does not indicate smaller tall buildings, but the height of surrounding big city centre area is bigger. In case of Loerrach, it is additionally interesting because in this case 3D void considers also profile of terrain – floor level of space in-between.

5.2. Type 2 – Typology by slope

Each 3D void has its unique triangular structure. All the 3D triangles have its own unique inclination resultant from Z coordinates of all 3 nodes linking elements of 'positive' part of virtual city model (buildings / structures). The aim of this type of parametric interpretation was detecting potential areas where tall buildings are located by changes in height (Z values) of 3D void. Assigning colour attributes to specific range of slope of triangles in 3D void allowed parametric analysis of public spaces focused on tracing of tall buildings and adjacent public spaces. Inclination of triangles indicates changes in heights of structures delimiting specific public spaces. It this case, the colour attributes were set up to 6 equal ranges of slope (triangles) using RGB palette from green (lowest inclination) to red (highest inclination).

Table 2 Table of colour attributes assigned to inclination of triangles – from green to red. (by author)

3D void	No. of colour ranges	Colour range for slope	RGB
Delft, Loerrach, Rotterdam	6 (equal)	Lowest: RGB 128,255,0	
		Highest: RGB 255,0,0	

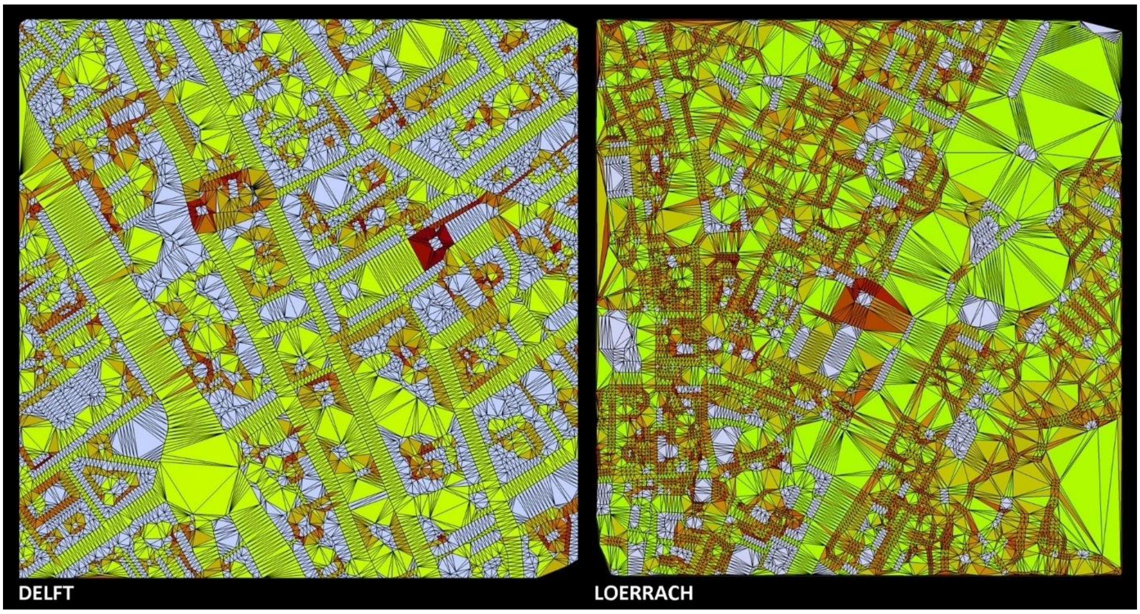

Figure 5 TBS – typology by slope for areas in Delft and Loerrach. Inclination of surface triangles marked with colour attributes. Parameterization performed on the basis of triangulation accuracy in GIS application. (by author)

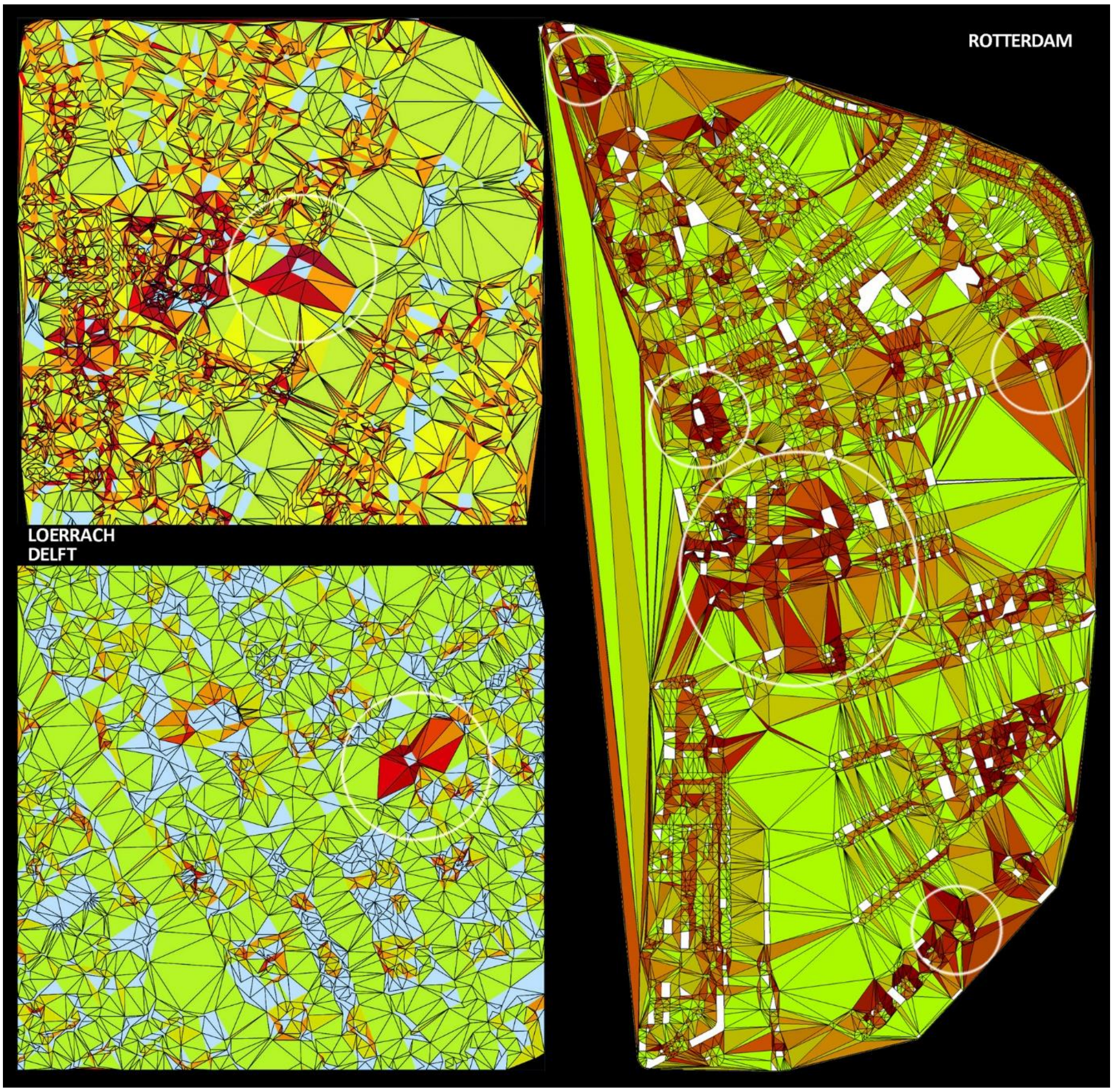

Figure 6 TBS – typology by slope for areas in Delft, Loerrach, Rotterdam. Inclination of surface triangles (highly inclined red triangles) indicating appearance of tall buildings and surrounding public spaces marked by circles. (by author)

Identical TBS analysis was performed on geometries generated in Quantum GIS and AutoCAD – to compare results and check triangulation processes (Figures 5,6). Presented samples show advantage of accuracy of data processed by Quantum GIS application. Light grey areas on figure 5 clearly show built-up environment against public spaces in-between in colour. Apart from slightly different detailed geometry of public spaces adjacent to tall buildings, both of TBS analyses clearly indicate locations of tall buildings within selected sites. Accuracy of 3D void in sense of triangular geometry also depends on procedure of generating point cloud (described earlier) – what density of points was estimated.

TBS parameterization is also useful because potential of imaging height structure of urban areas as indicating areas of irregular urban typology (height and size of buildings) by changes in inclination. It is partly visible on samples from Loerrach and Rotterdam – in Rotterdam mostly, because of very irregular building structure in the Stadsdreihoek area. On the left side of the Rotterdam TBS sample (fig. 6) some artefacts (odd long triangles) remain after irregular shape of selected area for analysis (also seen on fig. 7).

5.3. Type 3 – Typology by length

Third type of parametric interpretation of 3D voids between buildings aims at assessing data on spatial integrity and general morphology of public spaces. All the connections between vertices in generated point cloud (essence of triangulation) represent distances between components of urban structure (buildings, structures, etc.), but also trace dimensions and regularity of space between buildings. Length of these connections can be used for analysis in both ways, as 2D lines generated from flat Delaunay triangulation, or 3D lines of triangular surface of the 3D void. The 2D approach gives only width / length parameters of public spaces with respect to ground floors of surrounding buildings, but the 3D lines indicate also volume parameters. In the presented sample 6 ranges of length were estimated for creating TBL maps (in fact 7, but the lowest lengths up to 5 meters were automatically eliminated). Ranges were estimated after measuring general limit of length specific for dimensions of buildings – it was set as green colour (figure 7). The table below presents ranges of length of lines for analysis of triangular connections between generated vertices of point cloud.

Table 3 Table of length parameters generated with colour attributes from blue to red. (by author)

Range of length	RGB	Number of lines | **total length [m]** in range					
[m]		**Delft**		**Loerrach**		**Rotterdam**	
0-5		40086	**11583**	56699	**22848**	7710	**14787**
5-15		17644	**175179**	24535	**216736**	6761	**61024**
15-30		12481	**261709**	11610	**215946**	3692	**74577**
30-50		4159	**155948**	2933	**99057**	1164	**44241**
50-80		853	**50118**	894	**48430**	755	**47868**
80-100		66	**5646**	121	**10011**	139	**12183**
100-200		0	**0**	196	**20946**	129	**17387**
200+		0	**0**	50	**13321**	25	**6755**

Performed imaging of length parameters (figure 7) shows, that in case of Delft and Loerrach open spaces of diagonal over 80m surround or are located in direct neighbourhood of tall buildings. In Rotterdam density of tall buildings causes that such dimensions of open spaces appear not between but out of groups of tall buildings. Also the density of Delft results in no occurrence of lengths over 100m. In Loerrach, specific shape of high length area derives from localization of railway vast areas in the city. The case of Delft shows direct relation of tall building with main big open space in the city. Rotterdam is specific, because presented sample application of the method does not recognize water areas, because lack of cityGML terrain data.

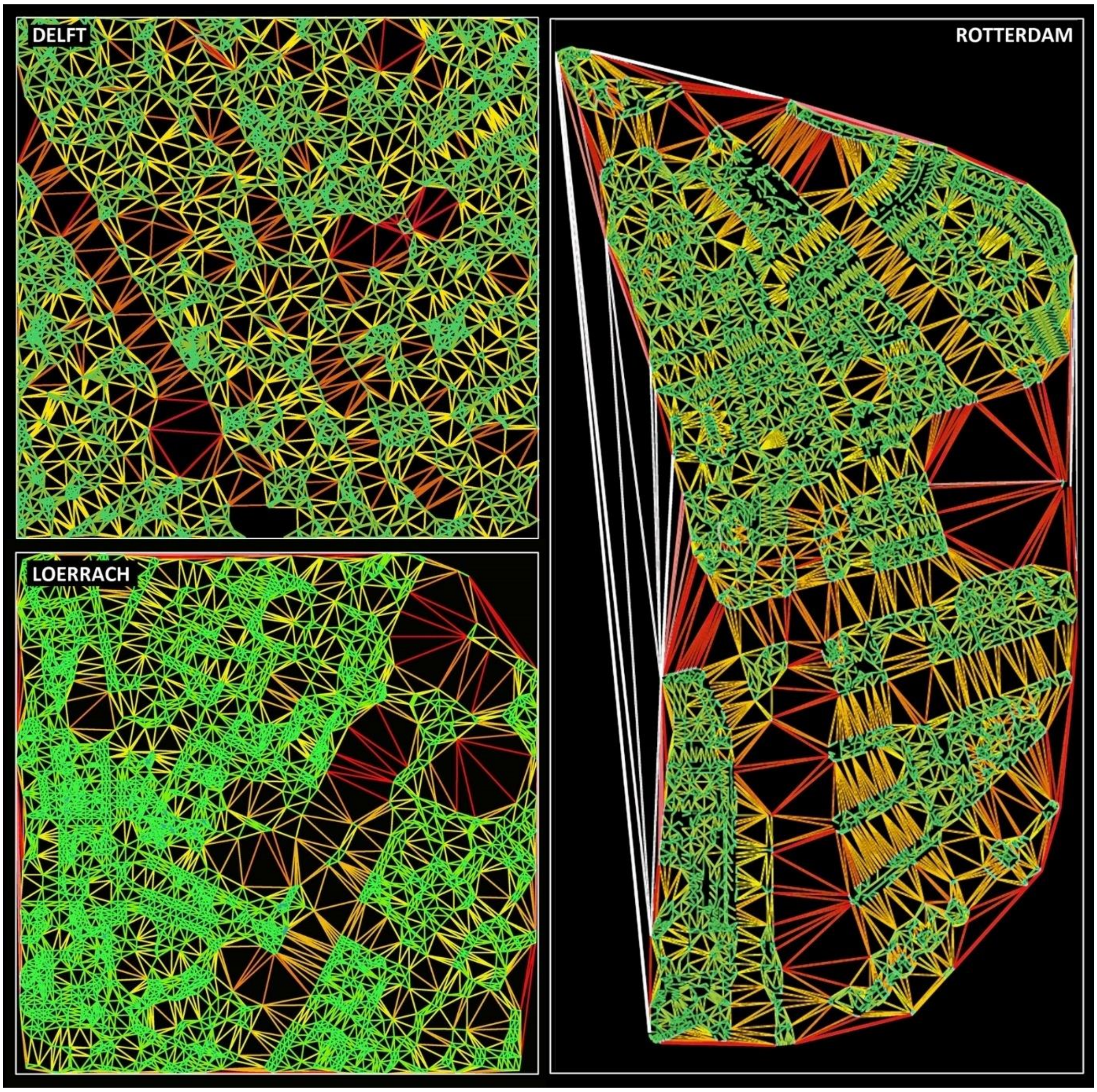

Figure 7 TBL – typology by length for Delft, Loerrach, Rotterdam – colours from blue to red. (by author)

5.4. Type 4 – Typology by area

Interpreting geometry of 3D voids by typology of areas in triangular solid bases on quiet similar concept to presented TBL concept, but for this type of analysis the geometrical base is 3D solid generated by extrusion of 3D triangular surface towards ground level (level of terrain). It is worth mentioning, that standard of data in cityGML provides a class of object called TIC – Terrain Intersection Curve, defining precisely points of interaction with terrain. TBA parametric interpretation does not consider areas overlapping surfaces of buildings in virtual city model because the 3D void is used after process of subtraction – which means, that 3D geometry within volume of buildings if removed before. The type of solid used for TBA is presented as last stage of process presented in figure 2. The setup of area ranges used to perform analysis is estimated for triangular shapes of 3D void, but the aerial parameters were doubled according to geometrical assumption that regular rectangular public space (e.g. square) can be represented by 2 adjacent triangles. The table below presents ranges of area attributes prescribed to triangular geometry to perform analysis.

Table 4 Table of estimated area ranges for TBA with distribution of results on selected areas. (by author)

Range of area	RGB	Number of components [triangles]		
[m^2]		**Delft**	**Loerrach**	**Rotterdam**
1-500		**removed**	**removed**	**removed**
500-1000		**675**	**352**	**272**
1000-1500		**111**	**52**	**66**
1500-2500		**37**	**37**	**42**
2500-5000		**12**	**35**	**66**
5000+		**0**	**0**	**36**

Figure 8 below presents maps of distribution of public spaces with TBA method. Clear pattern of public spaces is visible on the left, middle and right maps use combination of TBA with cityGML ground floor layer (representing buildings layout). The case of Loerrach indicates, that TBA in further perspective has to be adjusted by analyzing relation between number of points (estimated distance between points) generated in point cloud, because building density affects and distorts resultant geometry in aspect of size of triangles. The effect of Rotterdam city scale is also seen in results of TBA by number of public spaces bigger than 5000m^2 – in Delft and Loerrach undetected.

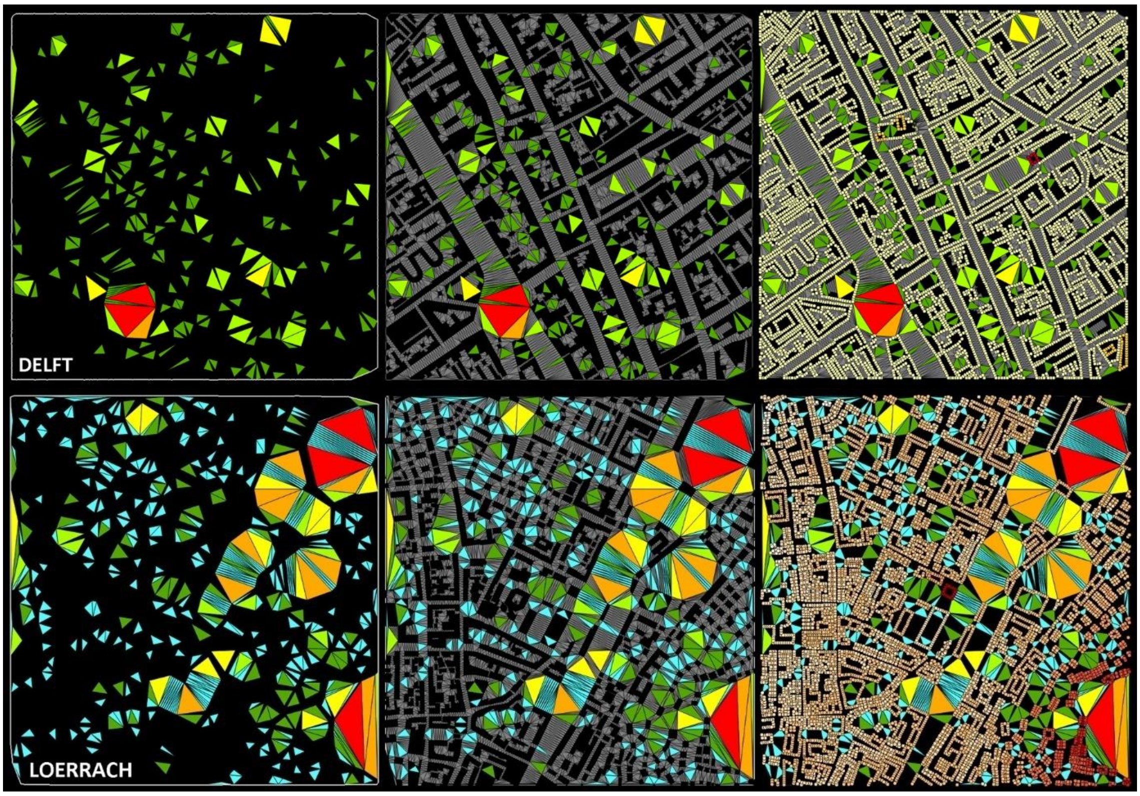

Figure 8 TBA – typology by area for Delft, Loerrach, Rotterdam – colours from blue to red. Clear pattern of public spaces (areas) on left, combination of TBA with buildings plan in the middle, combination of TBA with structure of building height on right side. (by author)

On the right side of figure 8, the result of TBA method was combined with map of building heights represented by points in colour from light to dark red due to value of Z coordinate (top points of buildings).

5.5. Type 5 – Perception issues

The last part of parametric approach to phenomena of space between buildings is related to much less measurable and parametric in fact aspects of perception. This type of interpretation is not only about geometry but its users as well. Generally, this part of 3D void analytic concept will be expanded and deepened in further perspective, but there are two selected sample issues presented in the paper. One of such parameters refers to impact of height of tall buildings on cityscape in general. The cityGML data set for virtual city model was used to generate (with support of QuantumGIS environment) raster map representing height of buildings in areas of Delft and Loerrach to provide kind of impression of impact of height structure on adjacent areas. According to rather low-height building structure of these cities, the impact of tall buildings on perception of public spaces is significant. In Delft, strong impact is generated by two tall building dominants of churches (Nieuwe Kerk and Oude Kerk), in Loerrach it is impact is less because of lower height of single tall building of Town Hall Loerrach. It is also visible how important is impact of landscape in this case (in the right corner of figure 9) – in Delft the flat landscape does not contribute to the perception.

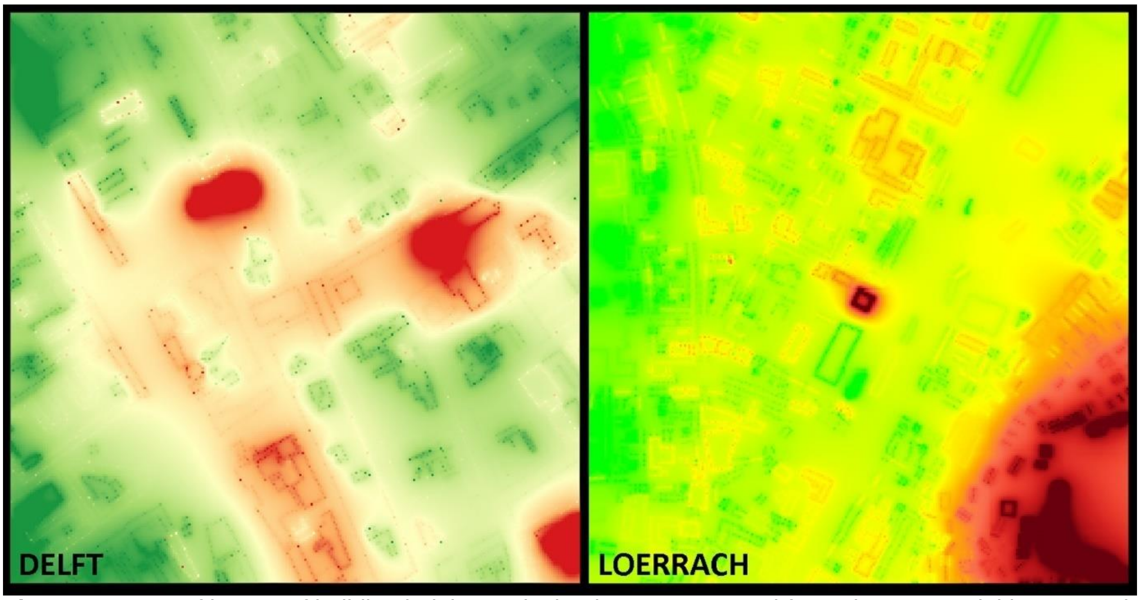

Figure 9 Raster of impact of building height on city landscape generated from cityGML model in GIS environment. Two dominants of churches in Delft on the left, single Town Hall Loerrach tall building on the right. (by author)

The last, but not least interesting aspect for perception of public spaces in urban structure is potential coming from natural sunlight accommodation capacity. This type or parameterization was generated using open source CAD software compatible with cityGML converted model. The sunlight accommodation capacity was calculated and imaged by number of sun hours collected by each 2 x 2m square piece of public space adjacent to tall building. The sample calculation was set up for area in Delft (simpler LOD2 cityGML model), and was performed for period of 30 days in month of September using daily time period of 11 hours (from 7:00 a.m. to 6:00 p.m.). The number of sun hours collected during this period is represented by gradient of colours from blue (lowest values) to red (highest values). Figure 10 shows result of analysis performed by free extension tool to CAD software for main square area at Nieuwe Kerk in centre of Delft.

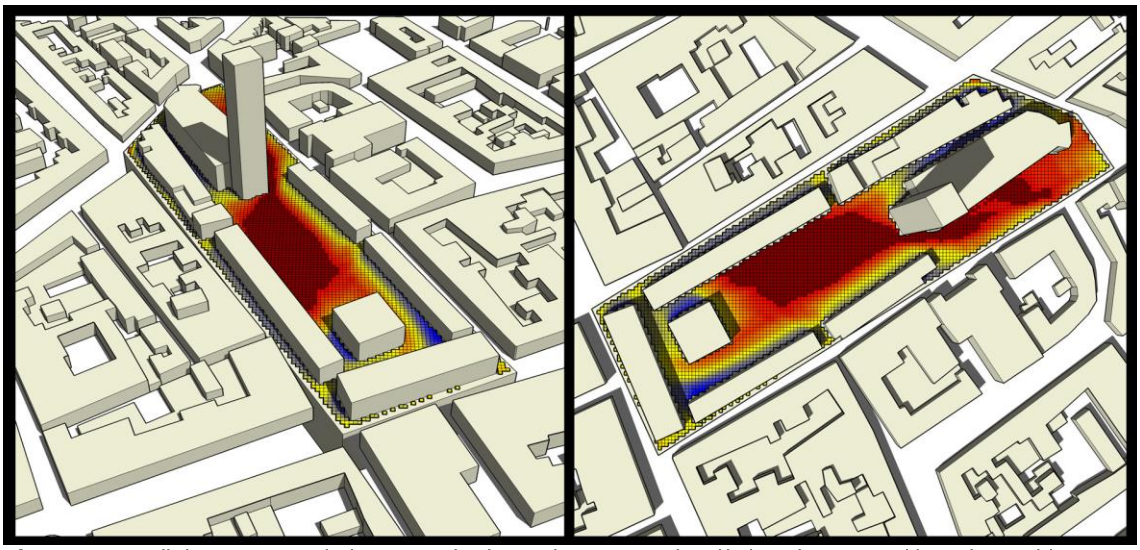

Figure 10 Sunlight accommodation capacity for main square of Delft (at Nieuwe Kerk) performed in LOD2 cityGML model converted into CAD standard. The number of sun hours indicated by colour gradient from blues to reds. (figure by author Sunhours / Sketchup)

6. Summary

Generating three-dimensional geometry of 3D voids is only very limited part of multi-aspect character of space between buildings. The proposal touches mainly geometrical issues of system of open spaces between buildings. The main technical challenge for further applications of the proposed approach is calculation of enormous geometrical data within virtual city models of entire cities. This application was tested on very limited area of 1 – 2 km^2. Apart from clearly defined level detail for cityGML models (LOD), there is still incoherence in spatial data from different sources. The very high geometrical accuracy can be only achieved by possibly uniform spatial data – this also remain a challenge in field of data import. However, the sample application of parametric interpretation of 3D voids shows perspectives for multi-aspect comparable study on urban morphology and space between buildings in different types of cities. The specific case of tall buildings in cities is very relevant because, as it is indicated by observation of 3D voids, there is close relation between localization of tall buildings and system of public spaces in different type of urban structures.

REFERENCES

BOOKS

Gehl, J., (2003), 'Space between buildings. Using public space', Copenhagen, The Danish Architectural Press, Fifth edition, ISBN 87-7407-283-8

Groot, R. and McLaughlin, J.D, (2000), 'Geospatial Data Infrastructure - Concepts, Cases, and Good Practice', Oxford University Press, Oxford

Donnay, J.P., Barnsley, M.J. and Longley, P.A., (2003), "Remote Sensing and Urban Analysis: GISDATA 9', CRC Press

Hillier, B. and Hanson, J., (1984), 'The Social Logic of Space.', Cambridge University Press, Cambridge

Gehl, J., Gemzøe, L., (2004), 'Public Spaces, Public Life.', The Danish Architectural Press, Copenhagen

Li, Z., Zhu, Q. and Gold, C. (2005), 'Digital terrain modelling: principles and methodology.', CRC Press, Boca Raton

Carr, S., Francis, M., Rivlin, L.G. and Stone, A.M., (1992), 'Public space', Cambridge University Press, Cambridge

Carmona, M., Tiesdell, S., Heath, T. and Oc, T., (2010), 'Public places, public spaces: The dimesions of urban design.", Routledge

JOURNAL ARTICLES

Páez, A. and Scott, D.M., (2005), 'Spatial statistics for urban analysis: A review of techniques with examples.', in: GeoJournal, Volume 61, Issue 1

Kolbe, T. H., (2009), 'Representing and Exchanging 3D City Models with CityGML.', in: Lee, J. and Zlatanova S. (Eds.), 3D Geo-Information Sciences. Springer-Verlag

Jiang B., Claramunt Ch. and Klarquist B., (2000), 'An integration of space syntax into GIS for modelling urban spaces.', JAG, volume 2, issue 3/4

Pal Singh, S., Jain, K. and Mandla, V. R., (2013), 'Virtual 3D city modelling: techniques and applications.', ISPRS 8th 3DGeoInfo Conference, Vol. XL-2/W2, Istambul

Szczepanek, R., (2012), 'Quantum GIS - wolny i otwarty system informacji geograficznej.', Czasopismo Techniczne zeszyt 4-Ś/2012, Wydawnictwo Politechniki Krakowskiej, Kraków

Czyńska, K., (2010), 'Tall buildings and harmonious city landscape.', Space & FORM, no 13, Szczecin 2010

Turner, A., (2000), 'Angular analysis: a method of quantification of space.', CASA Working Papers 23, London

Kolbe, T. and Bacharach, S., (2006), 'CityGML: An open standard for 3D city models.', Directions Magazine

Levy, A., (1999), 'Urban morphology and the problem of the modern urban fabric: some questions for research.', in: Urban Morphology, vol. 3/2, pages 79-85

CONFERENCE ARTICLES

Kolbe, T.H., Gröger, G. and Plümer, L. (2005), 'CityGML – Interoperable Access to 3D City Models'. In: Proceedings of the Int. Symposium on Geo-information for Disaster Management, 21-23 March 2005, Delft

Moser, J., Albrecht, F. and Kosar, B., (2010), 'Beyond visualisation – 3D GIS analyses for virtual city models.', ISPRS 5th International 3D GeoInfo Conference, Berlin, International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences

Pedrini, H., Schwartz, W.R. and Franklin, W.R., (2001), 'Automatic Extraction of Topographic Features Using Adaptive Triangular Meshes.', International Conference on Image Processing (ICIP-2001), Thessaloniki, Greece

Zwoliński, A., (2014), 'Complexity of public spaces system between key tall buildings in city of Szczecin - geometrical aspect of public spaces in 3D city model.', 16th International Conference on Geometry and Graphics (ISGG), Innsbruck, Austria

Zwoliński, A., (2014), 'A day in a shadow of high-rise – 3D parameterization and use of public space around PŻM / Hotel Radisson building complex in centre of Szczecin.', Architecturae et Artibus, vol. 6, Oficyna wydawnicza Politechniki Białostockiej, Białystok, ISSN 2080-9638, pages 67-71

Sevtsuk, A., (2013), 'Networks of the built environment.', in: D. Ofenhuber & C. Ratti, eds. [De]coding the Tity – How Big Data Can Change Urbanism, Birkhäuser

Kada, M., McKinley, L., (2009), '3D building reconstruction from LiDAR based on cell decomposition approach.', in: Stilla U, Rottensteiner F, Paparoditis N (Eds) CMRT09, IARPS, vol. XXXVIII, part 3/W4, Paris

OTHER

Sevtsuk A., (2010), 'Path and Place: A Study of Urban Geometry and Retail Activity in Cambridge and Somerville.', PhD dissertation in Urban Design and Planning, MIT, Massachusetts

Gröger, G., Kolbe, T.H., Nagel, C., Häfele, K-H., (2012), OGC City Geography Markup Language (CityGML) Encoding Standard, OGC

INTERNET

Geores	http://www.geores.de
cityGML	http://www.citygml.org/
cityGML data	http://www.bestel3d.nl/
web3D	http://www.web3d.org/
Quantum GIS	http://www.quantum-gis.pl/
GRASS GIS	http://grass.osgeo.org/