Chapter

Urbogeosystemic Approach to Agglomeration Study within the Urban Remote Sensing Frameworks

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Abstract

The spatial arrangement of human activity within urban areas is normally provided by areal management, and its effective provision is a complicated problem. The current urban development causes a number of problems and urgent challenges, which can be met and resolved exclusively on the basis of innovative scientific and technological advances. The main research objective of this chapter is to represent the authors' theoretic concept of the urban geographical system combined with the original Urban Remote Sensing approach based on the advanced technique of airborne LiDAR (Light Detection And Ranging) data processing. The authors attempted to prove that the presented concept could contribute to an understanding of the urban agglomeration as an urbanized spatial entity. The chapter explains in what way the urbanistic environment is a quasi-rasterized 3D model of actual city space, and the urbogeosystem (UGS) is a quasi-vector 3D model of the hierarchical formalized aggregate of UGS elementary functional units–buildings, both can efficiently simulate and visualize an urbanized area. Web-based geoinformation software for LiDAR data processing with the objectives of urban studies has been introduced together with its key functionalities. The population estimation use case has been examined in detail within the presented approach frameworks.

Keywords: urbanistic environment, urbogeosystem, urban remote sensing, LiDAR, automated feature extraction, web-based software, population estimation use case

1. Introduction

The continuing significant growth of population all over the world, but, first of all, in developing countries, forces scientists to seek new advances and solutions in Demography and Urban Studies domains. These two subject areas primarily mean increasing involvement of the innovative approaches and techniques related to geoinformation technology (GIS) and to the urban remote sensing (URS) field [1–3]. Since the continuing growth of the total world population takes place together with the phenomenon of urbanization, the relevant information systems intended for the survey of these two connected processes have to possess some bidirectional modeling and analyzing characteristics, which would overlap both demographic and urbanized issues.

We have just mentioned the significance of remote sensing data processing and GIS-modeling tools to the mentioned extent. This role can hardly be overvalued, taking into account that many from contemporary cities and their affiliated areas have become to act for several recent decades as more and more complicated *urban systems* with drastic dynamic changes within the relevant geographical space and with systemic specific impact on involved people movement and behavior [4–7].

If *an urban agglomeration* can be considered as a highly developed spatial entity of urbanized areas [8], then the approach of *the urban geographical system – urbogeosystem* (UGS) [3] should be applied for examining a number of relationships among the constituents of this system, which may definitely demonstrate its core feature – *the complexity.* Since the complexity is a key description of the contemporary urbanization process too, a whole issue of the spatial urban regularities may require to be evaluated by taking into account not only spatial but purely geographic issues. Both the mentioned rapid urbanization growth, and its attendant alterations in old, and in new cities do not allow to examine any other alternative to an acceptance of a city phenomenon as this just mentioned entity – *an urbogeosystem*, which operates within a certain extent of the geographic space.

It is also necessary to emphasize that the key characteristics of contemporary urban development, which has its effect in forming agglomerations, have caused a number of challenges that require innovative technologies in urban studies. These challenges and responses to them can be summarized in the following way [9]:

- With rapid development and alterations in urbanization, the studies of urban systems become more and more sophisticated;

- First of all - in developing countries, the number of cities has been substantially increased and the urban territories have been enlarged with a rapid speed in several years only;

- Fast-growing regions with a huge variety of extensive urban constructions become more and more numerous;

- A necessity for accurate terrain models for urban planning and landscape architecture as well as relevant sophisticated spatial data processing becomes quite necessary;

- A need for an effective automated survey of buildings to determine quantity and quality characteristics of changes that take place over some period of time;

- Provision of precise environmental monitoring over the key cities in the regions with an intention to obtain extensive data of the URS category: optical and infrared imageries, LiDAR (Light Detection and Ranging) point clouds, and radar imageries.

Although the urban areas cover only 2% of the globe surface in recent years, they include more than half of the world population, and consume more than three-quarters of the total generated energy. The latter produces more than 80% of the greenhouse impact [10]. It is understandable then, why a problem of optimized growth of urban settlements has been a major problem for residents, urban developers, and city authorities for many centuries already. The category of "urbanism" itself appeared more than a century ago [11], while the first statement that an urban agglomeration might represent the core definition in the theory of urbanism occurred with the introduction of the "megalopolis" entity in the middle of the twentieth century [12]. The author of this latest reference stated that routine urban areas gradually would transfer into mentioned megalopolises by joining and changing nearest semi-urban areas and rural neighborhoods. Monitoring this settlement growth became more and more complicated phenomenon, that was why some further research focused on the necessity of the urban system approach together with various sophisticated mapping techniques, which we have mentioned already at the beginning of this introduction [4, 6, 13].

Data of various remote sensing approaches, different GIS platforms, and modules provide the application of a variety of modeling techniques for resolving fundamental riddles related, for example, to spatial dimensions of the agglomeration growth. These techniques may belong to different scientific domains, e.g., fractals and theory of chaos [14], unsupervised classification [15], the algorithm of cellular automata [16], fuzzy logic [17], automated feature extraction [18], analytic hierarchy procedures [19], urban change detection [20], and several other ones. Even being quite diverse, all mentioned methodical solutions can effectively contribute to both estimations of the urban agglomeration expansion to the neighboring rural environment, and to the description of a relevant urban system according to key features of its internal and external relationships and impact.

The main **research objective** of this chapter is to introduce the authors' theoretic concept of the urban geographical system, and this concept is combined with the original URS approach to simulation of *the urbanistic environment* as a model of *a real city domain*. This urban remote sensing approach is based on the advanced technique of airborne LiDAR data processing. A use-case of population estimation on the base of building geometries and topology of urban space both modeled within the urbogeosystemic approach is described in detail in the finalized section of the chapter.

2. The concept of the urban geographical system

Earlier research completed in the fifties-seventies of the past century normally defined an urban system as not more significant entity, than a straightforward set of cities (or smaller settlements combined in a united urban territory) with some relations among these separate units. Nonetheless, there were two seminal books in the second half of the seventies, which represented some *regular structure* in the systems of cities [4, 21]. Probably, these publications were that trigger, which initialized actual urbo-systemic research somewhat later. The authors insisted, that they merely summarized within an applied perspective some concepts and methods, that had been developed as earlier as in the fifties [21, 22]. Although, all these publications, from our point of view, represented only few relevant research samples, which could be reliably determined as some phenomena of the pure emergent features of either a system of the city (separate districts within one urban area as a systemic entity) or a system of several different cities.

Introducing once a definition of an urban geographical system [3, 9], we attempted to extend and develop some basic ideas of the urban system delineation represented by various scientists in former publications [4, 6, 23, 24].

Empty city spaces between buildings and other infrastructural objects within urban territories are much more complicated according to their daily dynamics than they were even 10 years before. It means the schedule of these spaces filling during a day with residents, both static, and moving objects has altered drastically. By choosing the appropriate GIS-modeling technique we can simulate the mentioned dynamics and record it in a certain formalized mode within the frameworks of the model of the urbanistic environment mentioned above.

The urbanistic environment (UE) is a quasi-rasterized model of a continual nature of actual city space and this space key features, which can be visualized as a space limited by various surfaces and can be represented directly by these surfaces. Thus, it can be reasonable to suppose, that the UE also possesses a continuality of the object it represents. The UE continual nature can be contrasted with *the discrete nature of an urbogeosystem – the hierarchical formalized aggregate of elementary functional constituents of its natural analog, which may demonstrate some emergent (systemic) properties. The UGS can be visualized by various 2D vector graphical primitives on a plain (points, lines, polygons), and by quasi-vector 3D primitives in the three-dimensional space.* All emphasized 2D/3D primitives combine a particular *formalized view of the urban space.*

Taking into account modeling characteristics of UE and UGS, quasi-rasterized and quasi-vector ones, correspondingly, and referring to the essence of real objects both models represent – physical environment of a real city (modeled by UE) and sets of separate features in it (simulated by UGS), a research and developing procedural consequence *Initial/derivative data = > UE= > UGS* can be easily placed within the frameworks of raster-vector transformations. The latter is a subject of routine GIS functionality. Applying this functionality is the only understandable procedure, which can contribute to answering the question: if a given city does rather belong either to urban systems or to *urban sprawl* [25].

The first outlining of the urbogeosystem was suggested in our earlier paper and it laid in a completely ontological aspect. According to it, an urbogeosystem is "...The UGS is an urban system located within a definite extent of the geographic space; it is an unsustainable social-environmental system which is also a united entity of various architectural features and dramatically changed natural ecosystems..." [3, p. 110].

Those literature sources, that introduce various descriptions of *the urban system structure* [4, 6, 21–24, 26], imply each separate systemic component in a set of cities as *a point feature*, while interconnections and relations between each pair of these single objects – as *a linear feature*. Then a certain group of cities within the boundaries of a definite region, are located in a certain *areal feature*. Instead of "a city" as a separate unit, we can accept "a city ward (district)", then obtain a set of such units within a particular urban territory. In this way, we can enter a completely another research scale, but in both larger, and smaller scales points, lines, and areal fragments (regions or parcels) are key components of an urban geographical system. The geographical scalability can be applied then, while a single object (a city or a ward) is *a point* in one scale, but on another, larger scale it becomes *an area.* In a similar way, we can apply scalability to *the lines* and obtain the linear features of different magnitude [7, 9].

Let us assume that initially, a set of *N* cities indicates some *N*N*-matrix, in which "point cities" interact in different terms of human, industrial, trade, transportation, and information traffic, composing a picture of *an external urbogeosystem*. On the first step of scalability, a matrix would also define a number of linear features, which mirror spatial linkages in *an external urbogeosystem* in the mentioned terms. On the second scalability step, not the same, but similar matrix depicts *N* districts of one city only and all interconnection pairs among them, which exist in an *internal urbogeosystem*. In the simplest definition, it is a set of districts in one city, as we already mentioned.

On the basic fundamentals of the UGS approach introduced above, we elaborated and proposed *the algorithmic sequence of the UGS research with GIS tools* [3]. It consists of several algorithmic blocks that sustainably combine a thematic geographical model, urban remote sensing technique, and both basic and customized GIS functionalities. The key algorithmic blocks in this scheme are as follows (**Figure 1**):

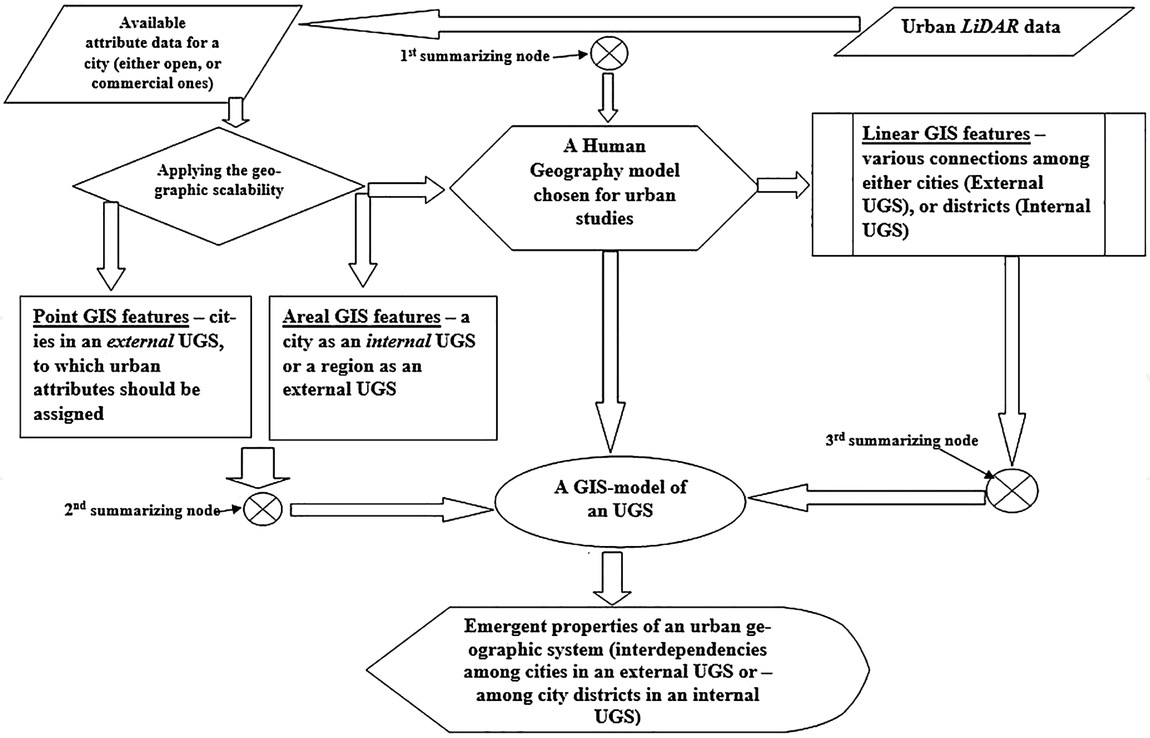


Figure 1.
The algorithmic flowchart of the UGS study with GIS tools [3, p. 111].

- Gathering with LiDAR and initial processing of the urban remote sensing data;
- Adding supplementary attribute data obtained from other than urban remote sensing sources;
- Choosing a thematic model for simulation of the city residents' behavior (a model from Human Geography or Geography of Population domains);
- Applying the geographic scalability and further delineation of point, linear, and areal features as the content of both an external, and an internal UGS;
- Composing an ultimate GIS-model of an urbogeosystem, which consists of two components: a quasi-rasterized model of the urbanistic environment, and, in fact, a quasi-vector model of an urbogeosystem;
- Adding available attribute data (semantic data, as a rule) to a model of the urbogeosystem and generating derivative attributes for this model (geometric attributes and metadata, as a rule);
- Finalized results of applying UGS-approach as delineation of various emergent properties for a given urban territory. These results can be employed for various thematic use-cases in different municipal and other applications.

We have already published several papers in the urbogeosystem approach, examining various aspects of this concept: its basic fundamentals [3], its applicability to the Smart City concept implementation [9], its possible involvement in the multifunctional approach to the 3D city modeling [27], some from UGS-basics were applied to the structural analysis of agglomerations in Kharkiv region (Ukraine) [28]. The latest research accepted a well-known definition of agglomeration as a large city (as an agglomeration core) with all its nearest townships and

#	Agglomeration hierarchical level	A settlement as an agglomeration center	Topical SGS/corresponding urbogeosystem
1	Mega-level	A large city (nearly or over a million of residents)	Interregional, regional SGS/*internal UGS of the first rank*
2	Macro-level	A city as a center of *an oblast* – a larger territorial administrative unit in Ukraine	Regional SGS/*internal UGS of the second rank*
3	Upper meso-level	A town as a center of *a rajon* – a smaller territorial administrative unit in Ukraine	Under-regional SGS/*internal UGS of the third rank*
4	Lower meso-level	A town, a township as a center of a united territorial community	A united territorial community as an SGS/*internal UGS of the fourth rank*
5	Micro-level	A township, a large village	Local SGS/*internal UGS of the fifth rank*

Table 1.
The corresponding agglomerations and urbogeosystems hierarchy for the Ukrainian population settlements (an updated table from [28, p. 4950]).

the suburbs. We attempted to define that all these settlements are characterized by various interrelations. Thus, a new entity of aggregated functioning appears, which is common for this big urban territory, and for small towns and villages around it. This urbanized compact entity of settlements was accepted as a spatial systemic formation with all relevant features of the urban geographical system. Therefore, it can be reasonable to apply to an agglomeration study that algorithmic flowchart presented in the illustration above (**Figure 1**). Socio-geographical survey over the East of Ukraine, in particular – within Kharkiv region, proved that agglomerations as spatial patterns of different hierarchical levels can be delineated, not only as social geographical systems (SGS), but also as both external and internal urgogeosystems, and they are significantly present in the territorial arrangement of this region. Taking into account the general concept and the surveyed results, we suggested the hierarchy of the delineated agglomerations with respect to the necessary update of the territorial division of Ukraine (**Table 1** is updated from [28]). Thus, a regional system of settlements has been proven to be not only a mosaic of all five agglomeration levels, which may overlap each other in the spatial extent but also – *the spatial hierarchy of urbogeosystems*. Consequently, the local agglomerations are the urbogeosystems of the fifth, lowest rank. In other words, they are basic units, elementary ones in the common hierarchy for both urbogeosystems, and for agglomerations. It follows from **Table 1**, that various hierarchical levels of the settlement spatial structure can be distinguished – from microlevel to mega-level, and these levels correspond to a particular social geographical system, and to a particular urbogeosystem.

Concluding the second section of this chapter, which has introduced the UGS approach with this example of agglomeration research, it is necessary to address the following issue. This approach can be directly provided for examining agglomerations according to its main features introduced in this chapter section:

- gathering, combining, and processing urban remote sensing data, in particular – LiDAR point clouds;
- choosing an applicable Human Geography and Demography models;

- refining derivative digital information and converting it into the GIS-primitives;
- defining geospatial aspects of all interrelated contents and conditions of actual urban environment, and consequently generating in three steps *quasi-rasterized model of urbanistic environment* = > *quasi-vector model of urbogeosystem*= > *model of agglomeration clusters.*

Further in this text, we examine some steps of this consequence more in detail, while taking it for granted, that a strong spatial aspect of the urban research necessarily implies the GIS/URS processing procedures, tools, and operations efficient involvement in this research, what we attempt to outline as various issues in the text below.

3. Urban remote sensing with LiDAR for digital cities

3.1 Automated feature extraction

Automated reconstruction of the sets of various buildings is yet a serious challenge on the way to 3D digital city modeling. Other significant tasks can be affiliated with it, for example, outlining the Smart City concept implementation [9]. Exactly for the two latest decades, LiDAR data and its processing results have become real alternative data sources to optical and multispectral imageries with respect to generating a three-dimensional representation of urban territories [2, 29, 30]. Being able to collect straightforwardly dense and accurate 3D point clouds over both urban, and rural features, the technology of the LiDAR survey provides a reliable and beneficial data source to this end. Almost all LIDAR devices are either Airborne types (ALS, aircraft-based) or Terrestrial (Mobile, MLS) (vehicle-based), as well as drone-platform ones.

The key processing and simulated procedure intended for building digital cities, while the latter is a basic fundamental for urbogeosystem delineation, is the *automated feature extraction* (AFE) from point clouds generated by LiDAR [31]. Normally the automated feature extraction is based on both optical satellite images of high resolution, and on LiDAR datasets generated by airborne, terrestrial, and drone platforms on regional surveys [32]. The latter ones are usually provided by strips and then combined as three-dimensional point clouds [2]. AFE output is the key tool that makes digital urban models. Various approaches, methods, and solutions that *detect*, *extract*, and *generate* building models with any selected alternative technique, all compose a highly significant research domain [33].

This latter statement can be accepted by default, because a whole approach mandatory means 3D automatic, but desirably - *smart mapping* of the multi-scalable urban environment, that is of the extreme complexity. Moreover, as it has been mentioned already if exactly LiDAR data become in recent decades an efficient alternative to imageries obtained by traditional satellite remote sensing, then this data source should become a subject for various approaches and algorithms, as previously traditional URS was. These approaches and algorithms should differ for various procedural stages, and suggest robust solutions separately for 1) building detection, 2) extraction and 3) building reconstruction steps [34].

The automated building/other infrastructural feature extraction procedures can be fulfilled by three sub-procedures, as was already stated above, i.e., building detection, building extraction/segmentation, and building reconstruction [34–36]. All three sub-procedures mentioned may not be clearly distinguishable. To complete a single stage of automated extraction of buildings may not yet be satisfactory enough for practical applications due to the great complexity of actual urban architecture, which we always face while modeling the urbanistic environment on the first step of the urbogeosystem delineation. Different additional sophisticated algorithmic solutions should be involved, for example, those ones, which assist in distinguishing between building constructions and urban vegetation, while processing an airborne point cloud [37].

Traditionally being within the frameworks of our original multifunctional approach to LiDAR point cloud processing [27, 31, 38, 39] we have to consider only those methods, which use exclusively LiDAR data, so that to utilize the building geometric and topological properties only, and not any other urban landscape characteristic except *urban topography*. In this way we have to pass through the mentioned above trinity of steps: building detection, segmentation, and reconstruction ones, while topography is generated upon the first step from these three while discriminating so-called "ground" and "non-ground" points when processing LiDAR datasets.

It is commonly accepted understanding that the model, which includes not only the ground as the topography, but other features – the discrete ones, is not a digital elevation model (DEM), but *a DSM – a Digital Surface Model.* According to existing references before the sustainable usage of LiDAR point cloud for topographic modeling, the digital surface model was normally calculated using various imageries, hybrids (imageries + point clouds), and feature pyramids [40]. The final DSM surface is refined then on the base of local adaptive regularization techniques provision. While the urban topography has been generated already, the building detection step is grounded on the fact that buildings, as a rule, should be higher than the neighboring topographic surface. This is normally estimated using various mathematical morphology techniques through the DSM [41].

In our original approach to LiDAR point cloud processing with the intention to separate "ground" and "non-ground" point as a mandatory premise for further non-ground features detection, segmentation, and reconstruction, we have provided the following steps, which can be introduced in the following summarized way proceeding from several relevant references [27, 31, 39]. The initial unique step assumes the delineation of both DEM and a DSM from the airborne point cloud raw data, in which point density should be preferably within a range of *10–80 points per square meter*. The proposed method of DEM generation accomplishes a classification of the original data as "ground" points versus "non-ground" points by robust estimating procedure, which has been described in detail in one of our latest papers [39]. In all consequent algorithmic steps of modeling UE, the *heavyweight models* generated by triangulation and interpolation, and *lightweight models* generated by clustering and segmentation are used, but not the original data points. DEM is subtracted from the DSM. The output results of building detection and segmentation, i.e., the delineation of individual building footprints can be provided with a connected component analysis. A set of the selected feature candidate regions can be arranged. Then a planar surface segmentation can be executed, is based on the analysis of the DSM vector variations. The output result of this step is crucial for finding planar parcels of buildings. These parcels are expanded then by applying a bunch of the region growing algorithms. The neighborhood connections of these parcels are determined, and a simplified model resembling the roof structure in a certain building is generated. A Voronoi diagram can be created for extraction of neighboring joints and connections of numerous facets that compound roofs and walls in the heavyweight models, while planar segmentation and customized topological rules are used for segmenting and combining lightweight models of simplified buildings with gable roofs.

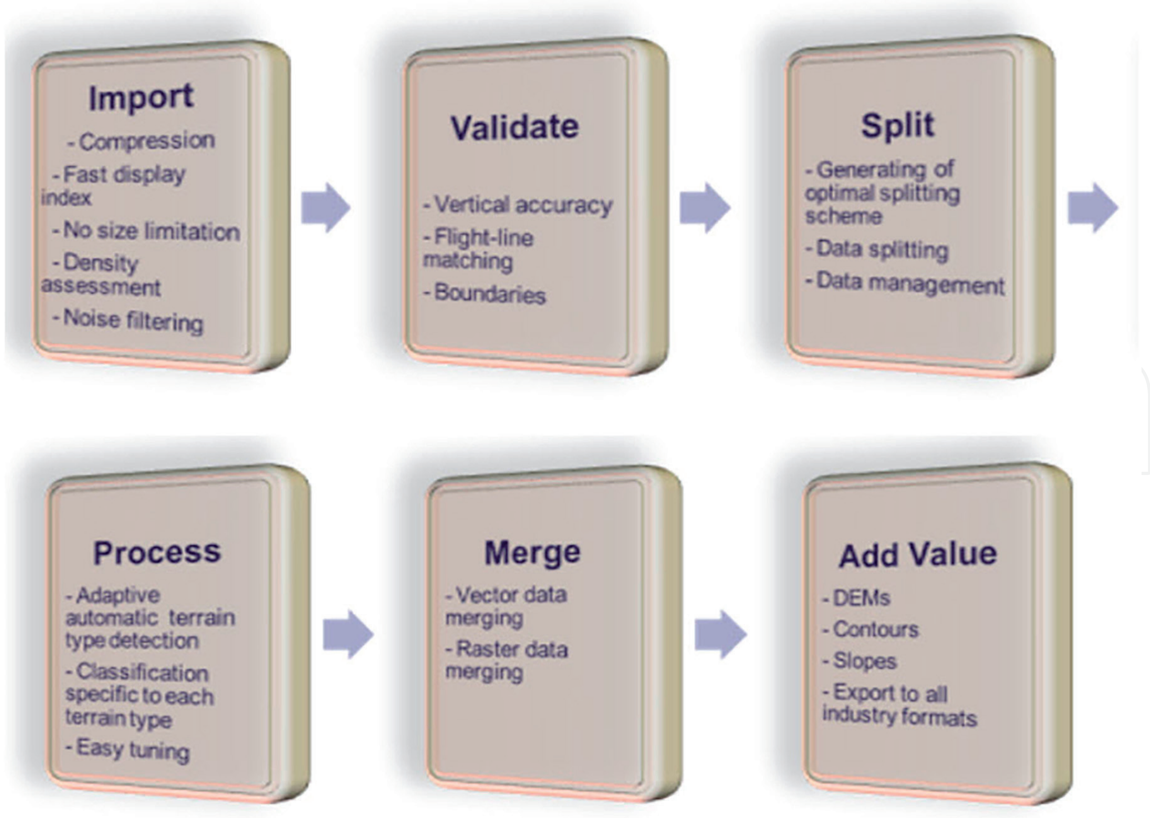


Figure 2.
Some key constituents of the AFE-pipeline are intended for the generation of both urban topographies, and building models from LiDAR point clouds.

A summarized AFE-pipeline relevant to LiDAR data processing, which contains some of the basic fundamentals presented in this subsection, is visualized on the following flow-chart composed by this chapter authors (**Figure 2**):

The flowchart presented not only depicts the main components of the automated feature extraction pipeline but also is some kind of a presentation due to the digital city content creation. The latter with the introduced UGS approach consists of two phases, as we already explained:

1. modeling the quasi-rasterized UE, and

2. simulating the quasi-vector UGS.

Both phases contain in one way, or in another all six blocks of this flowchart. Nonetheless, the *first phase* (directly affiliated with modeling the UE) does definitely include the *urban data mining* complex (*Import*, *Validate*, and *Add Value* blocks), while *the second phase* implies the implementation of pre-processing, processing, and simulating solutions (*Split*, *Process*, and *Merge* blocks) for the presentation of the three-dimensional geometry of each separate building and sustainable topology for the sets of buildings in a digital city. The output results of the flowchart, which is in **Figure 2**, may be provided in several formats, e.g.,. gLTF,. K*LM*,. D*AE*,. B*3DM*, etc. Nonetheless, a core inner format is. *OBJ.* Simulated features of a digital city are produced with the representation of their borders. A whole *3D urban scene* can be depicted as a set of building constructions with the continuality of their bounding walls, vertices, edges, and supplementary outhouses, and this continuality can be described by certain parameters of *urban geometry*. In this way, the urbanistic environment is simulated. Due to the mentioned continuality, a scene can also demonstrate the topological interdependencies of buildings

Building Extraction Rural Area
Task name: Wash_DC_2106_2206_2107_2207_2...

Level of detail:
● Boxes
☐ Shadows ☐ Labels

757 models

☐ model_0028

Extent size X:	135.33 m
Extent size Y:	88.46 m
Extent size Z:	28.20 m
Basement area:	10128.29 m²
Altitude:	6.89 m
Latitude:	38.83 °
Longitude:	-77.02 °
Quality:	acceptable

Figure 3.
The urbanistic environment and a fragment of the UGS modeled for a district of Washington, D.C. (USA) and visualized in the interface of a cloud processing platform: EOS LiDAR tool – ELiT cloud.

among themselves and with non-housing urban features and various infrastructural objects. Urban features are visualized according to the *CityGML* LODs (Level of Detail) standards [42].

Thus, a partial fragment of an internal urbogeosystem can be modeled and visualized in the 3D scene with spatial, geometric, and semantic characteristics, which can be exposed for each selected feature, or for a number of them. A number of LOD 1 (a simplified box-model of a building) models that correspond to the CityGML 2.0 concept are visualized for the Washington, D.C. urban area in the interface of a web-GIS software, in which elaboration participated both of this chapter authors. This interface sample relates to the cloud processing platform of this software (**Figure 3**).

Our models of urban objects exposed on the illustration above possess all necessary characteristics of 3D digital city models. While many other three-dimensional objects seem to be predominantly used for display, it is reasonable to emphasize that these simulated features presented in a 3D Scene can be increasingly employed in a number of domains within a large range of tasks beyond the direct visualization. Such perspectives can be opened if we accept simulated sets of building models as the aggregations of elementary functional features of an urbogeosystem. The reasonability of such an assumption has been proved by the authors in some previous publications [3, 9, 39].

3.2 Web-based geoinformation software for the urbogeosystem approach implementation

We have already mentioned that both authors of this chapter participated in research and development (the first author – as ahead of this R&D) of the web-based and cloud-based versions of the geoinformation software focused on LiDAR data processing for urban studies, what took place in the EOS Data Analytics Company (https://eos.com/eos-lidar/). Common fundamentals of the Automated Feature Extraction determine our core algorithmic structure named as the *High Polyhedral Modeling* (HPM) and elaborated within the frameworks of the integrated *BE (Building Extraction) /BEF (Building Extraction with Footprints) /CD (Change*

Detection) /DEM-G (Digital Elevation Model Generation) functional pipeline of ALS/ MLS data processing [27]. HPM produces building models with numerous facets.

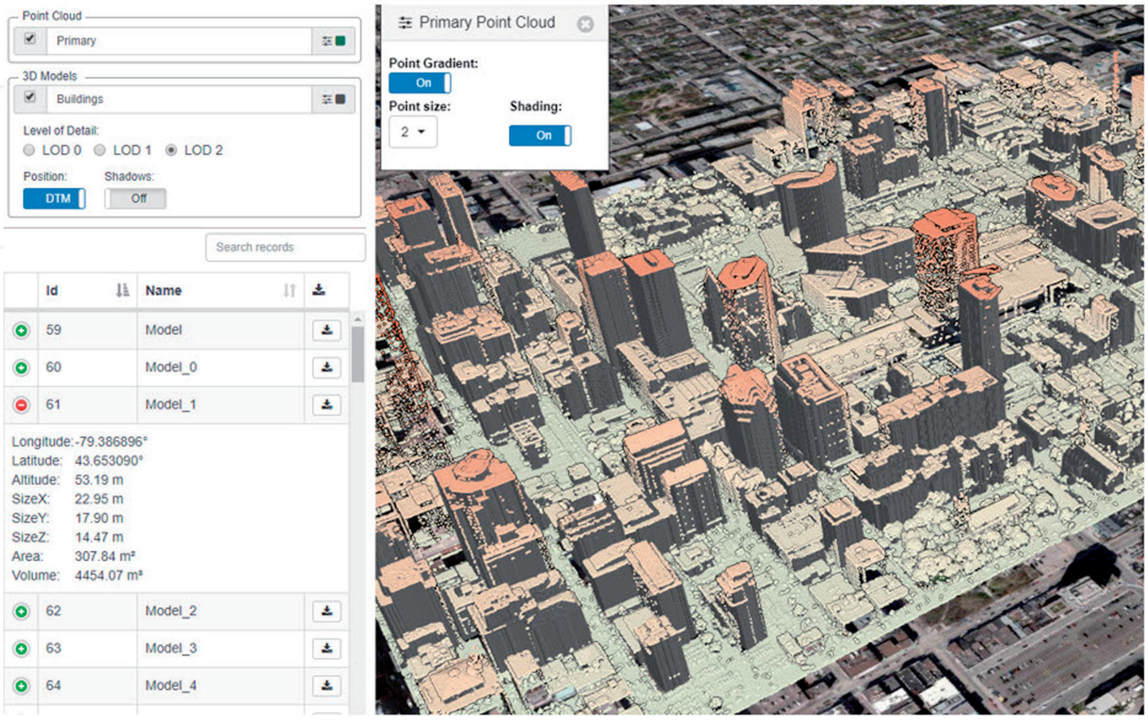
According to the whole HPM workflow, two following problematic issues may occur with great probability: #1 – to provide more precise classification of both “vegetation” points, and “building” points is crucially necessary; # 2 – to elaborate a definite method in what we have to define the building topological and geometric properties in those cases when point cloud data are incomplete. All possible solutions for both issues should be preliminary outlined, and we took it into account while developing our basic original algorithm of LiDAR data processing and proposing some supplementary technique that has to be accomplished in parallel with core algorithm operation.

Within frameworks of our conceptual R&D approach buildings are accepted as the key man-made features in the modeled urbanistic environment. According to the HPM output results it consists of numerous continuous surface segments (polyhedrons) that compose *the trinity content of the city space*: urbanized topography, building surfaces, and empty urban spaces between buildings that are separated by two previous issues.

There are two platform versions on which *EOS LiDAR Tool*, *ELIT* software, can operate: a cloud processing version, as *ELiT Cloud*, that applies to AWS instance service power (**Figure 3**), and a typical client–server, web-based application as *ELiT Server*. The urbanistic environment of Toronto-City as a model reconstructed by the HPM pipeline may look like follows in the *ELiT Server* interface (**Figure 4**).

Corresponding functional tools of both *ELiT*-software platforms, which are set within the HPM frameworks are *BE*, *BEF*, *CD*, and *DEM-G* tools. The *BE/BEF* tools extract *original building footprints* from point clouds while modeling [39, 43].

In addition to the High Polyhedral Modeling, we have developed the alternative AFE-technique, such as is the Low Polyhedral Modeling (LPM) approach, which is based on procedures of planar segmentation and clustering of LiDAR point clouds rather, than on their classification (in the case of HPM). The LPM technique is primarily intended to extract low-rise buildings of either rural areas, or city suburbs



Point Cloud
☑ Primary

3D Models
☑ Buildings

Level of Detail:
○ LOD 0 ○ LOD 1 ● LOD 2

Position: DTM
Shadows: Off

Search records

	Id	Name
⊕	59	Model
⊕	60	Model_0
⊖	61	Model_1

Longitude: -79.386896°
Latitude: 43.653090°
Altitude: 53.19 m
SizeX: 22.95 m
SizeY: 17.90 m
SizeZ: 14.47 m
Area: 307.84 m²
Volume: 4454.07 m³

	Id	Name
⊕	62	Model_2
⊕	63	Model_3
⊕	64	Model_4

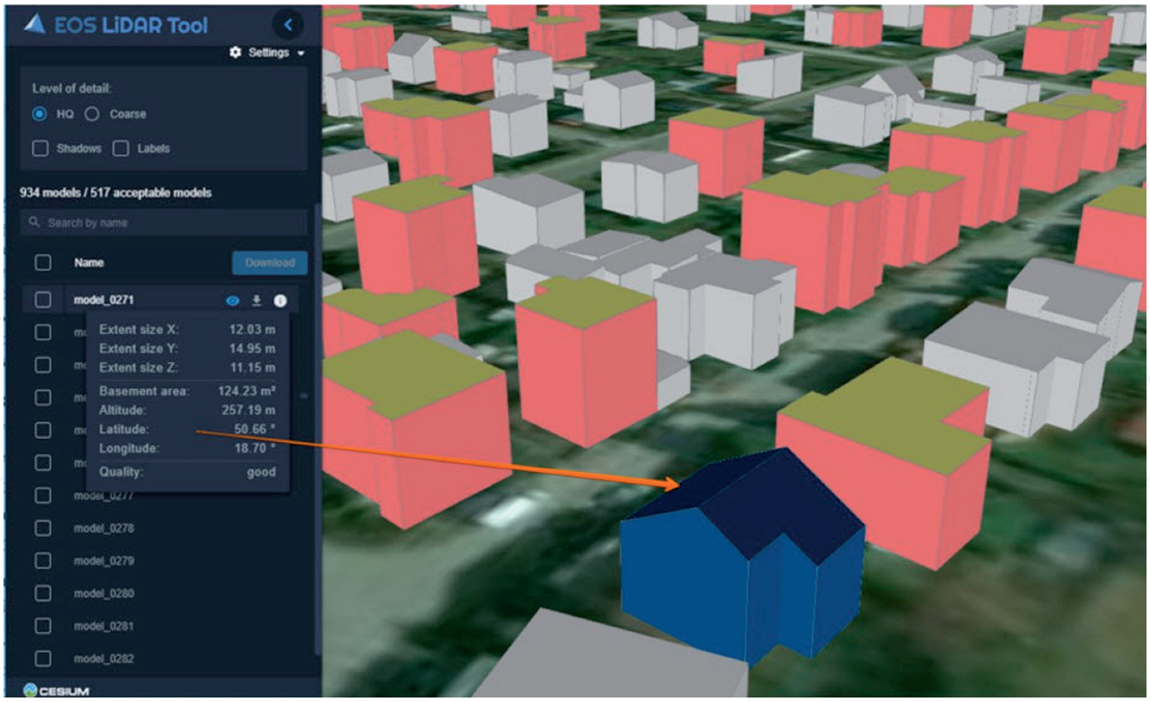
Primary Point Cloud

Point Gradient: On

Point size: 2

Shading: On

Figure 4.
The UE of Toronto-City (Canada) is modeled in the ELiT server interface.



934 models / 517 acceptable models

Extent size X: 12.03 m
Extent size Y: 14.95 m
Extent size Z: 11.15 m
Basement area: 124.23 m²
Altitude: 257.19 m
Latitude: 50.66 °
Longitude: 18.70 °
Quality: good

Figure 5.
Lightweight models of elementary functional constituents of the urbogeosystem of Lubliniec-City (Poland) in the ELiT cloud processing platform interface.

as light-weighted models, which consist of only a few facets. The relevant functional tool of the LPM approach is the *BERA (Building Extraction Rural Area)* tool. The *BERA* instrument employs *the third-party building footprints* while modeling [39, 43]. If the HPM-technique with its *heavyweight models* is more preferable for simulation of the quasi-vectorized UE (**Figure 4**), then the LPM-method – for creation of the 3D quasi-vector *lightweight models* of buildings and other features as elementary functional constituents of a certain urban geographical system (**Figure 5**).

If not taking into account such research entities as UE and UGS, but evaluating only building modeling itself, then it can be emphasized, as we have already mentioned above, that the BERA functionality is an application for detection, extraction, and modeling of low-rise housing located in city suburbs and urban areas. The HPM approach is recognized to be more efficient for simulating high-rise buildings of downtowns.

Contrary to HPM, with which the BE tool is affiliated, this alternative AFE technique, LPM, and the *BERA* tool, as it has been already underlined, are strongly based on planar segmentation, clustering, and reconstruction of polyhedral building models. In comparison with the HPM pipeline, both planar segmentation and clustering substantially decrease the number of polyhedrons as constituents of a building model extracted. Thus, we attempted to provide an efficient update and an applied realization [43] of the advanced theoretical approach known as segmentation and reconstruction of polyhedral building roofs [18].

Both software, a client–server application, and a cloud-processing platform can be run from a web browser installed on a user's workstation. According to its architectural scheme, the *ELiT* software performs transmitting procedures between the Processing Core, that is on a server, and a Client, while providing such operational sets as Data Management (uploading, downloading, etc.), Task Management, and interactions between the Core and a database. Finally, a Client provides a user graphical interface and the building model/topographic surface visualization. A Java Script based library - *Cesium 3D Tiles* is employed for this display, https://cesium.com/

4. Population estimation and mapping on the base of elementary functional units of an urban geographical system

Urbanistic environment and urbogeosystem modeling on the base of automated building feature extraction, further mapping of extracted and reconstructed features, and finalizing 3D digital city generation for both urban, and rural areas can be highly essential for many industrial applications. It would be reasonable to define four next key categories of the urbogeosystemic approach in its applied perspective. Each of these categories may directly relate to an agglomeration study: 1) common urban planning and design, urban environment visualization, promotion and learning of urban information, 2) specific urban planning, 3) those usages that are not directly related either to planning, or to visualization, for example, city population estimation as an operational procedure "on fly", that can be completed on any date between census, 4) commercial sector and marketing, including infrastructure, facility services related to specific urban information visualization, and urban data mining.

The range of those industrial applications that are pertinent, for example, only to *BE* and *BERA* building extraction functionalities may be lengthy enough: urban and municipal planning, augmented reality for gaming industries; environmental planning and monitoring, insurance policy and procedures, optimization of transmitter placement for telecommunication, locational based services, navigation, housing simulations, urban microclimate investigations, and shadow estimation. In all these use cases a building model is the primary object of interest, while exactly the sets of these models examined within the frameworks of the urbogeosystemic approach can, in our opinion, act as those elementary functional constituents of the actual city environment, which compose its *adaptive renewal cycle* with all four basic functions: *exploiting*, *conserving*, *releasing*, and *recognizing* [44]. These functions can be efficiently defined with the UGS approach, if we consider urban (agglomeration) growth in the context of this cycle, while also applying to spatial morphology, as those authors to whom we have just referred to, suggested once.

The point of view introduced in the above paragraph can be accepted as a forcible argument for choosing exactly *a set-of modeled buildings-level* for an urban population estimation use-case as a dominant one in a perspective of that agglomeration research, to which the UGS approach could mostly contribute. If an urban agglomeration is "...the future spatial organization of cities" [8], then any proven method of robust estimation of the population on the base of the urban spatial morphology are expected to be valuable enough.

Taking into account the routine public scarcity of real population values in various city district configurations of a real city, any more or less reliable procedures for evaluating numbers of residents between two censuses, which temporal gap may be up to ten and even more years, can hardly be overvalued [39]. Therefore, even an approximate estimation within a certain selected AOI may be highly necessary for optimizing routine municipal management. It has been evidently proved by the latest events in urban areas due to the modern pandemic phenomenon.

If we accept both separate buildings, and the sets of them as elementary functional urbogeosystemic units within a certain geographical extent of a city, then it is evident that not only different linkages caused by people movement between these sets combined in modeled city districts should be taken into account for calculating a number of residents in a certain area-of-interest (AOI), but also – building geometries themselves. The latter parameters can be the most precisely reconstructed just by LiDAR data processing, which proves the applicability of our approach to agglomeration research in overall extent. The UGS approach to population estimation has been supplemented by some existing methods of GIS /urban remote sensing application within this use case. This GIS/URS application is mainly concerned with the urban block- and census track-level of a number of residents calculating [45–48].

In one of our former publications, we have already presented "the step-by-step building space-metric method (BSMM) of population estimation" [39]. This method presents the series of procedures for any AOI, block, and district population estimations based on the building geometric and city space topological parameters derived from airborne LiDAR data processing. As it has been stated in the second section of this chapter, **Figure 1** summarized our whole research workflow, in which the BSMM was accomplished within three following consequent blocks: 1) *A Human Geography model…* = > 2) *A GIS-model of an UGS* = > 3) *Emergent properties of an internal UGS (interdependencies among city districts in an internal urbogeosystem)*. The blocks *Urban LiDAR data* and *Available attribute data for a city* were completed even before this BSMM block-trinity 1)-3), and their output was transferred through the first and the second summarizing nodes to *A GIS-model of a UGS* block (**Figure 1**). *Point-*, *Linear-*, and *Areal GIS feature* blocks are locked to the second block of the mentioned trinity. A whole introduced configuration of blocks is based on building a model produced by two blocks: 1) *A Human Geography model…* = > 2) *A GIS-model of a UGS*. This model is used for the calculation of interactions due to people movement among city districts and *census tracks* in the internal UGS. Geoprocessing aspect of the methodology introduced in this paragraph consists in adding population data to the metadata of. O*BJ* files presenting building models, and then visualizing in a *Cesium Scene* by the gradient color method.

A study area and data sources are related to the city of Boston, Massachusetts state, USA, and overlapped most of this urban territory. While completing the *ELiT* Geoportal web resource [39], we applied to airborne LiDAR data of open access as to one of the USGS projects available from: ftp://rockyftp.cr.usgs.gov/vdelivery/Datasets/Staged/Elevation/LPC/Projects/USGS_LPC_MA_Sndy_CMPG_2013_LAS_2015/laz/. The relevant census data were available from the U.S. Census Bureau's Web site (http://data.census.gov/), and from the Bureau of Geographic Information (MassGIS) site – the regional data of the 2010 U.S. Census [49]. A seamless, Massachusetts statewide digital map of land use has been taken from [50]. We assumed that it would be possible to obtain the territorial distribution of the population from UGS elementary functional units – the building models and *their affiliated volumes.* The BFT- parameter – Building Function Type (first of all – *residential, non-residential*) has been used as a key semantic attribute. Because of the lack of reliable semantic data and a certain vagueness of a particular building belonging to a certain land-use class, we had to apply to the original technique of automated definition of building type by its topology and geometry [39]. In total, the following stages complete the whole URS/GIS-tools pipeline of population estimation within the urbogeosystemic approach with BSMM:

1. *The preliminary data preparation stage* for population estimation on the basis of the UGS approach with LiDAR data processing was like follows. LiDAR point clouds as **.LAZ* files were downloaded from a few USGS projects through the web reference mentioned above. Building footprints were downloaded from the Open Street Maps (OSM) resource https://developer.here.com/products/data-layers?cid=. All footprints were combined in a united.*SHP* file by the *Save as* =>. S*HP* tool, which can be applied for any vector layer in the *QGIS 3.10* GIS platform. This combined file might contain information about 1) building population counts, and about 2) classes of buildings (a class of residential ones and a few classes of non-residential buildings – commercial, industrial, educational). This information can be available from the OSM footprints, but footprints with it overlapped not more, than 5% of their total number only.

Thus we have to apply to alternative information sources from [49, 50], as we have already mentioned above. Thus, after completing the preliminary stage of the population estimation use case we obtain the following:

- three polygonal layers as *.*SHP* files with the U.S. Census 2010 data [49] on the following three levels (both continuous, and random census blocks are used as samples): 1) census parcels; 2) sets of blocks; 3) separate blocks and sub-blocks; for each layer population data are stored in *"POP100_RE"* field;

- a statewide polygonal layer with boundaries of the land use classes [50].

2. *Modeling the urbanistic environment with a number of quasi-vector models* in it. The *BERA* tool has generated more than 350,000 City GML LOD1 models within a selected contour of the urbanized Boston territory. Thus, those sets of. O*BJ* files that can be associated with census parcels, blocks, and groups of blocks, have been obtained. Further, possessing already generated *.*OBJ* files, we have to add census information to them.

3. *Enriching.OBJ file*s of *UE-quasi-vector features with census information*:

- A point layer with geographic coordinates of each *.O*BJ* has been created. It contains the centroids of building footprints. The *BERA* tool has also generated for each *.*OBJ* a *.*JSON* file of the same name (an ordeal model number or *OSM_WAY_ID* of its footprint), and this *.*JSON* contains various metadata for a model, e.g. a computed volume of a building. We have added to the metadata dictionary the key *population* and a quantitative value for it.

- Using a customized Python script, we have processed all *.*JSON*-files in the *BERA* output folder and stored resulted data in a *.*CSV* file with a header as: *name, latitude, longitude, volume.*

- Importing a.*CSV* file to *QGIS 3.10* (menu *Layer= > Add Layer= > Add delimited text layer*), where all points presenting models have been localized, while names and volumes have become their attributes.

- Layers of land use and census tracks have been added to a *QGIS* project. Thus, for example, all models can be added to a *2D* map so that to define spatial belonging to a certain class (**Figure 6**):

In the same way as on the visual above, a layer of building models has been placed on the census parcels.

- The layers of point models, land use, and census parcels have been reprojected into *EPSG 26919* (a projection of.*LAS* files relevant to the territory of Boston) with the *QGIS* tool *Geoalgorithms= > Vector general tools= > Reproject layer*.

- The *Land use class* parameter has been recorded in a point layer of models by the tool *SAGA= > Add polygon attributes to points* (field *LU05_DESK*). According to the rule, *Polygon contains point* a point layer has accepted the information about a land-use class for any model as a point.

- Then a record of a population value of each census parcel or block should be provided as a semantic attribute for each model point, which falls into this

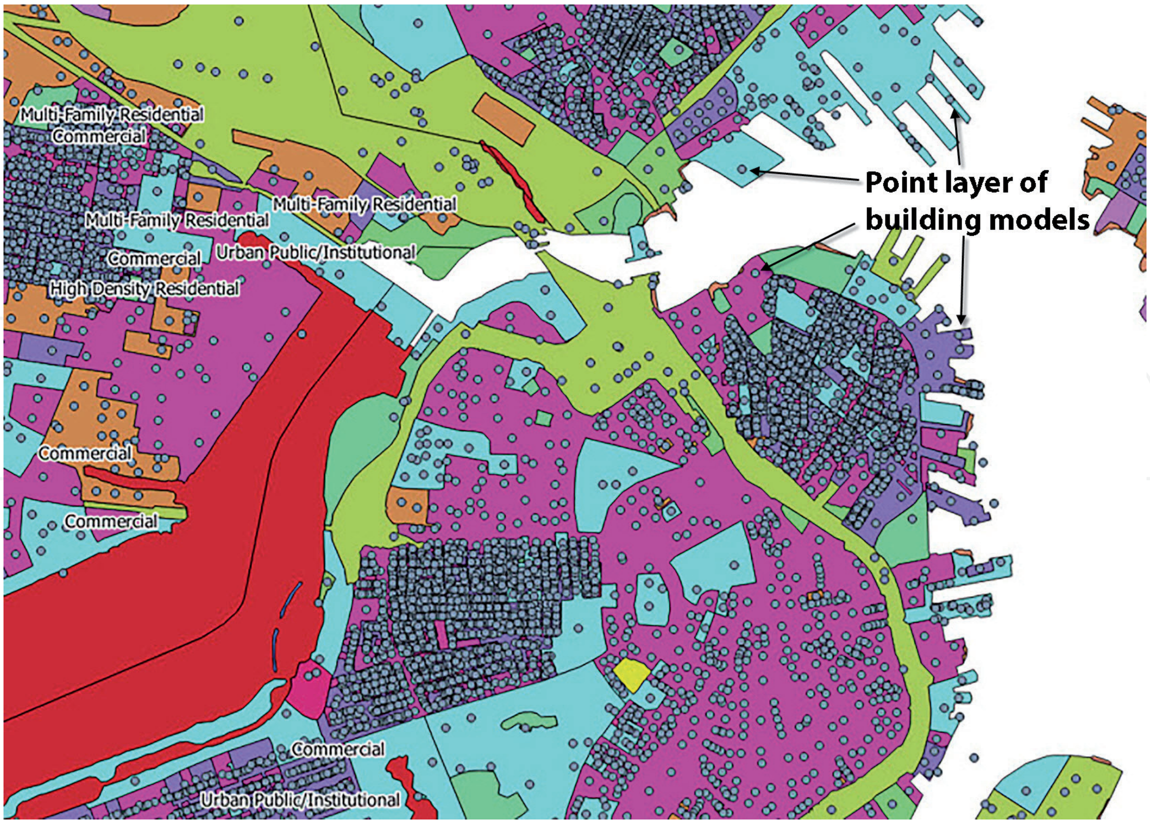


Figure 6.
Visualized in the QGIS-interface the points of building models (footprint centroids) located through different classes of land use in a fragment of the urbanized territory of Boston. The complete land use legend is available from [50].

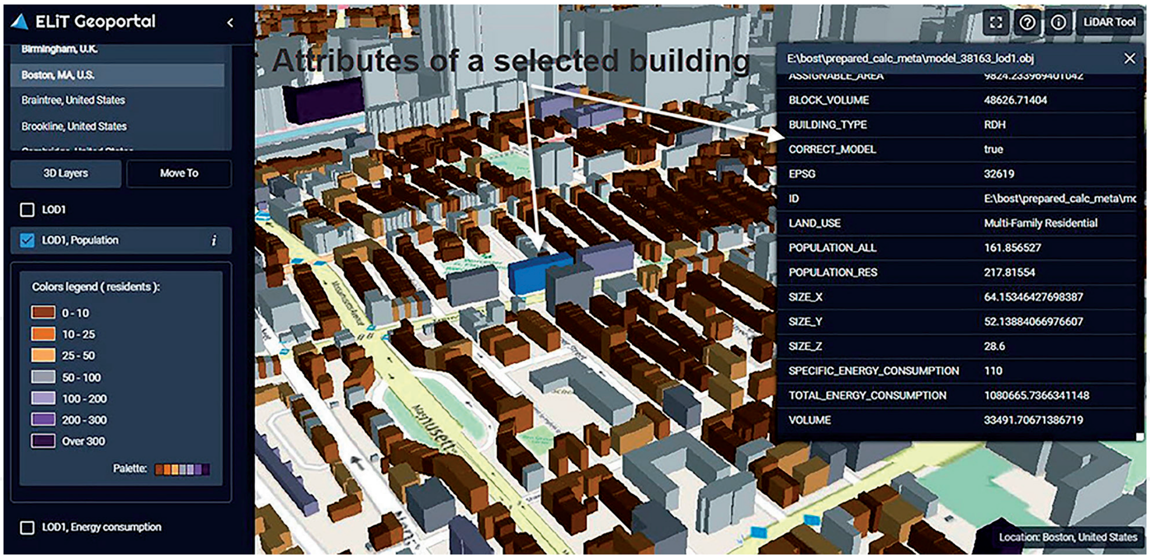
area. A procedure is completed with the *SAGA= > Add polygon attributes to points* tool. A new file in the point layer attribute table is titled in the same way with the attribute table of the census parcel layer - *"POP100_RE"*.

- A summarized volume of residential buildings for each census parcel should be further provided. Firstly, it has been necessary to use the tool *Select features using an expression* with a query *"LU05_DESK" like '%Resident%'*. Secondly, by the tool *SAGA= > Points statistics for polygons* total volumes of residential buildings have been calculated for each census parcel. Thus, a layer of census parcels has been obtained with a supplementary field – *SUM_volume* (a total residential buildings volume for each census parcel).

- Just as in 3.6 and 3.7 items the polygonal layer information has been recorded in a point layer: a total volume of residential buildings has been recorded in each building centroid (the field *SUM_volume*) that falls in this census parcel.

- The finalized correcting coefficients have been introduced for the sets of buildings located in various census parcels (field *COEF*). These parameters have attempted to take into account the major trends of people movements. It may actually reflect the population spatial distribution dynamics in an internal urbogeosystem, that took place after the latest census, and it was extrapolated from changes that actually occurred between two former censuses. Input for such evaluation can be based both on the information available from [49] and on some supplementary data sources.

- A new float-field has been added to a point layer table – *bldng_popul*. It has computed a ratio through all other fields of this point layer table:



E:\bost\prepared_calc_meta\model_38163_lod1.obj

ASSIGNABLE_AREA	9824.233969401042
BLOCK_VOLUME	48626.71404
BUILDING_TYPE	RDH
CORRECT_MODEL	true
EPSG	32619
ID	E:\bost\prepared_calc_meta\mc
LAND_USE	Multi-Family Residential
POPULATION_ALL	161.856527
POPULATION_RES	217.81554
SIZE_X	64.15346427698387
SIZE_Y	52.13884066976607
SIZE_Z	28.6
SPECIFIC_ENERGY_CONSUMPTION	110
TOTAL_ENERGY_CONSUMPTION	1080665.7366341148
VOLUME	33491.70671386719

Figure 7.
Resulted from the URS/GIS pipeline stages 1–4 visualization of the building population distribution in the urbanistic environment of Boston-City presented in a 3D scene of the ELiT cloud processing platform interface.

bldng_popul = (*volume*POP100_RE*COEF/SUM_volume*, where *volume* – a building volume, *POP100_RE* – a population value for a given census track, in which this building falls in; *SUM_volume* – a total volume of building in a census parcel.

- *The finalized attribute table* should contain the following fields: model *name* (obtained on step 3.1.); model *volume* (step 3.1); *LU05_DESK* (land-use class obtained on step 3.6); *POP100_RE* (census parcel population – step 3.7); *SUM_volume* (a total volume of residential buildings in a census parcel - step 3.8); *COEF* (correcting coefficients due to probable people movement – step 3.10); *bldng_popul* (estimated for a period between census a number of residents in each building – 3.12).

4. *Combined visualization in Cesium 3D Scene of the ELiT software interface* of those results obtained upon the second and third stages of the URS/GIS pipeline – an attribute table from 3.12 has been visualized as a 3D scene. In this way, the urbanistic environment and a viewed fragment of the UGS of Boston-City are presented with the building population distribution evaluated on the base of the urban architectural morphology (**Figure 7**).

While implementing a population estimation use case, it is reasonable to take into account, that some computed extreme numbers of residents can be caused by the errors in the input land use data. For example, a large residential building has been prescribed to the commercial or to any other non-residential class of land-use, while being actually in one census parcel with another, much smaller residential building, and there are only two these buildings in a given parcel. The small building, being prescribed to the residential class properly, has accepted a whole number of residents in a parcel, and a number of residents is drastically exaggerated then.

5. Conclusions

This chapter has introduced the original conceptual research approach concerning the urban geographical system, which is based on urban remote sensing with LiDAR data processing. The authors have made an attempt to prove that the presented methodology and techniques might contribute to the scientific understanding of the urban agglomeration as a highly developed spatial aggregation of urbanized areas. The urbanistic environment as a quasi-rasterized 3D model of actual city space, and the urbogeosystem as a quasi-vector 3D model of the hierarchical formalized aggregate of UGS elementary functional units – buildings, both can efficiently simulate, visualize, and represent an urban agglomeration according to its all representative criteria. The algorithmic flowchart of the UGS study within the suggested approach has been provided, and further research introduction has been affiliated with flowchart blocks.

The URS/GIS pipeline of making a digital city with LiDAR data processing has been examined mainly within an automated feature extraction perspective. In particular, it has been illustrated by the AFE-flowchart of some key processing constituents related generation of both urban topography, and building models from LiDAR point clouds. The possible scheme of digital city creation might consist of two consequent steps: 1) modeling the quasi-rasterized UE, and 2) simulating the quasi-vector UGS.

Web-based geoinformation software for LiDAR data processing due to the objectives of urban studies, in general, and agglomeration research, in particular, should demonstrate its optimal architectural solution as both a client–server application, and as a cloud-processing platform. The latter applies to AWS resources. HPM-technique provided by this software is preferable for the urbanistic environment modeling, while its LPM-method – for model generation of elementary functional units of the UGS – buildings. Each one from the row of software tools – *BE*, *BERA*, *CD*, and *DEM-G* can contribute in a particular perspective to agglomeration research.

Mentioning several thematic applications, which can potentially be resolved within the frameworks of the presented approach, we selected and examined in detail the building population estimation use case as the most relevant one to agglomeration research. A number of building residents, as a rule, are not widely available due to security and privacy reason. Thus, the suggested technique can significantly assist not only in an AOI-population estimation between census but also, e.g., in predicting the agglomeration growth in both short-term and long-term perspectives.

Appendices

AFE	Automated Feature Extraction
ALS	Airborne Laser Scanning
AOI	Area of Interest
AWS	Amazon Web Services
BE	Building Extraction
BEF	Building Extraction with Footprints
BFT	Building Function Type
BERA	Building Extraction Rural Area
BSMM	Building Space-Metric Method
CD	Change Detection
DEM	Digital Elevation Model
DEM-G	Digital Elevation Model Generation
DSM	Digital Surface Model
ELiT	EOS LiDAR Tool
HPM	High Polyhedral Modeling

LiDAR	Light Detection and Ranging
LOD	Level of Details
LPM	Low Polyhedral Modeling
MLS	Mobile (Terrestrial) Laser Scanning
SGS	Social Geographical System
UE	Urbanistic Environment
UGS	Urban Geographical System
URS	Urban Remote Sensing

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