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URBAN REMOTE SENSING WITH LIDAR FOR THE SMART CITY CONCEPT IMPLEMENTATION

С. В. Костріков. ДИСТАНЦІЙНЕ ЛАЗЕРНЕ ЗОНДУВАННЯ УРБАНІЗОВАНОГО СЕРЕДОВИЩА ДЛЯ ІМПЛЕМЕНТАЦІЇ КОНЦЕПЦІЇ «РОЗУМНОГО МІСТА». *У статті розглядається методологічна послідовність впровадження Концепції «Розумного Міста» (КРМ) - від удосконалення і подальшого розвитку її окремих теоретичних положень до визначення заходів щодо її практичної імплементації через ГІС-моделювання і просторовий аналіз міського (урбанізованого) середовища на підставі даних дистанційного лазерного зондування.*

На підставі значного літературного огляду розглядаються як запити і виклики щодо досліджень урбанізованих територій, взагалі, так і щодо КРМ, зокрема. Робляться уточнення і узагальнення окремих положень цієї концепції. Урбогеосистемний підхід подається сталою методологією, яка може суттєво додати до успішної реалізації КРМ. З точки зору цього підходу наводиться авторська дефініція категорії «Розумне Місто».

Розроблена і подається методична послідовність робочого процесу «дистанційне зондування – лідар – ГІС» для формалізованого відтворення «розумного міського середовища». Розглядаються ГІС-інтерфейс та функціональність оригінального програмного веб-застосування із обробки лідар-даних. Зокрема, подається домашня веб-сторінка з трьома головними функціональними інструментами: Виокремлення архітектури забудов та іншої інфраструктури міста; Визначення динамічних змін у міських забудовах; Генерація топографічної поверхні міста. У якості тільки кількох із множини можливих прикладів розглядаються п'ять сценаріїв (use cases – англ.) застосування програмного забезпечення для впровадження КРМ. На завершення узагальнюються результати дослідження, робиться наголос на необхідності розробки ключового компоненту системи підтримки прийняття рішень - бази геоданих для «урбанізованого геоінформаційного простору».

Ключові слова: *лідар, дистанційне лазерне зондування, урбанізоване середовище, геопросторова площина концепції «Розумне Місто», інтерфейс і функціональність веб-застосування ГІС, сценарії застосування програмного забезпечення, система підтримки прийняття рішень.*

С. В. Костриков. ДИСТАНЦИОННОЕ ЛАЗЕРНОЕ ЗОНДИРОВАНИЕ УРБАНИЗИРОВАНННОЙ СРЕДЫ ДЛЯ РЕАЛИЗАЦИИ КОНЦЕПЦИИ «УМНОГО ГОРОДА». *В статье рассматривается методологическая последовательность реализации Концепции «Умного Города» (КУГ) - от усовершенствования и дальнейшего развития ее отдельных теоретических положений до определению по определения мер по ее практической имплементации посредством ГИС-моделирования и пространственного анализа городской (урбанизированной) среды на основании данных дистанционного лазерного зондирования.*

На основании значительного литературного обзора рассматриваются как проблемные моменты и вызовы, касающиеся исследований урбанизированных территорий, вообще, так и относящиеся к КУГ, в частности. Делаются уточнения и обобщение отдельных положений этой концепции. Урбогеосистемный подход предлагается в качестве устойчивой методологии, которая может существенно поспособствовать успешной реализации КУГ. С точки зрения этого подхода дается авторская дефиниция категории «Умный Город».

Разработана и представлена методическая последовательность рабочего процесса «дистанционное зондирование – лидар – ГИС» для формализованного моделирования «умной городской среды». Рассматриваются ГИС-интерфейс и функциональность оригинального программного веб-приложения для обработки лидар-данных. В частности, представлена домашняя веб-страница с тремя основными функциональными инструментами: Выделение архитектуры застроек и другой инфраструктуры города; Определение динамических изменений в городских застройках; Генерация топографической поверхности города. В качестве только нескольких из множества возможных примеров рассматриваются пять сценариев (use cases – англ.) применения программного обеспечения для реализации КУГ. В завершение обобщаются результаты исследования, подчеркивается необходимость разработки ключевого компонента системы поддержки принятия решений - базы геоданных для «урбанизированного геоинформационного пространства».

Ключевые слова: *лидар, дистанционное лазерное зондирование, урбанизированная среда, геопространственный аспект концепции «Умный Город», интерфейс и функциональность веб-приложения ГИС, сценарии применения программного обеспечения, система поддержки принятия решений.*

Introduction of the problem. Global urbanization remains one of the most challenging present and future problem in the world. Moreover, the humankind probably still has not realized the multiple dimensions of this phenomenon. The world urban population has increased dramatically from 751 million in nineteen fifty to 4.2 billion in two thousand eighteen, according to the document issued by UN DESA [1]. This report also emphasizes that, despite its relatively lower level of urbanization in Asia, there are located up to 55% of the urban population of the world. There are numerous intriguing facts about the cities over the globe in different publications that merit attention. Thus, the tenth part of the population lived in thirty metropolises several year ago yet, while six hundred of cities possessed the world population quarter then [2]

Thus, the continuing significant growth of urban population all over the world, but, first of all, in Africa, Asia, and Latin America, forces us to seek

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for new advances in the Urban Studies domain, what primarily means to involve new approaches and techniques in the Information Technology and Urban Remote Sensing. Since the majority of developing countries are situated in the Tropical and Subtropical geographical belts, the drastic effects of that local urbanization on the tropical environment and the global climate deserve the closest attention [3]. Thus, remote sensing data processing and modeling tools, that may assist in urban studies, can hardly be overvalued. The First Earth Observation Summit issued in 2003 a declaration to organize the ad hoc international Group on Earth Observation (ad hoc GEO). The GEO plan has established a framework paper announcing the Global Earth Observation System of Systems (GEOSS) and outlined nine areas of its social benefits [4]. Quite a few publications have appeared since then, which contribute to the GEO Strategic Plan, while one of the most significant texts among all of them, in our opinion, is a book on remote sensing on sustainability [5].

GEO started a working plan a “Global Urban Observation and Information” Initiative since 2016. The top-managers of this initiative arranged six main aims for the period up to 2025 [6]. The key features of the contemporary urban development have caused a number of challengers that require the innovative technological introductions in urban studies. These challengers and the innovations have been already summarized in one of our previous papers [7]:

- With prompt development and changes of urbanization process, the studies of urban systems are also becoming more and more complicated;
- The number of cities increased and the urban territories have been enlarged with a rapid speed, especially in developing countries;
- Fast growing regions with extensive urban constructions become more and more numerous;
- A necessity for accurate terrain models for urban planning or related sophisticated spatial data processing becomes quite understandable;
- A need for effective automated buildings survey to determine quantity and quality characteristics of architectural changes that took place over time is accepted as a mandatory component of urban monitoring;
- Precise environmental surveys over the key cities in the regions with extensive remote sensing data analysis should be regularly provided.

Despite the urban areas cover only 2% of the globe surface in the latest years, they possess more than half of the world population, and consume up to three quarters of the total produced energy, which, in its turn, generates more than 80% of greenhouse effect [8]. Thus, it is evident that a problem of optimal development for urban settlements has been a major problem for their residents, builders, and municipalities since past centuries. The definition of “urbanism” itself was introduced as long ago as at the end of the nineteenth century [9]. This definition was already considered then as a delineated category of transforming urban slums into the livable environment with the goals of delivering it into sustainable one. The source, we have just referred to, made an origin of quite a few publications, but the book “City: its growth, its decay, its future stands alone in this row [10]. Practically, just this book introduced the understanding of *smart cities as distinct entities*, also it employed somewhat another lexicon for description those geographical spaces intended to improve city livability and workability. That in contemporary terms means – to make a city to be more *sustainable.* Actually “Sustainable Cities” and “Digital Cities” were those intermediate benchmarks, through which “the Cities of the Future” category has been transformed into *the Smart Cities* fundamental idea [11]. The IBM Corporation was really the first institution, which began to develop the *Smart City concept (the SCC)* within the frameworks of its “Smarter Planet initiative” by the end of the first decade of this century, when the drastic economic crisis burst out [12]. The first Smart City advances have been summarized as an integration of the modern technologies, features of urban sustainability, and social implication [13].

The ultimate **research goal** of our paper is to represent an effective multifunctional approach, which would combine the author’s urbogeosystem theory [7] with the Urban Remote Sensing (URS) technique for LiDAR (Light Detection and Ranging) data processing provided by the original web-based GIS-software [14]. Such combined attempt contributes both to the theoretical clarification of a city role as a driver for all environmental and urban systems, and to the applied implementation of the Smart City Concept.

The key elements of the Smart City concept within a geospatial perspective. Since exactly *the geographic information of urban development* such as maps of regional topography and vegetation, infrastructural network maps and census maps is highly necessary for the SCC implementation exactly because of *this concept's definite geospatial perspective*. Precisely this affiliation (a geospatial perspective ⬄ the Smart City concept) implies at least *three basic assumptions* and up to *five key elements.*

Firstly, the innovative methods, in particular, *the urban remote sensing* for the relevant geodatabase content are mandatory to be involved.

Secondly, the original theoretical approach, e.g., *the concept of urban geographical systems* has to be chosen for an effective processing pipeline construction in a case of a robust and consistent implementation of the SCC. These both first, and second assumptions have been already highlighted in the introductory section of our paper.

Thirdly, those *key elements* of the SCC, that directly connected with its geospatial perspective, should be delineated, explained, and listed. This is being done in this section of the paper.

The huge number of publications in the SCC domain have appeared only for few recent years. It looks like to be some problem to choose the necessary core elements of this concept from a tremendous number of relevant definitions made. Due to existing thoughts, such key element as *an innovation* can be selected as a leading one in the general outline of this approach [15]. The key constituents of this extended review of the Smart Cities's working definitions include: "A city well-performing in a forward-looking way…" [16, P. 8]; "A city that monitors and integrates conditions of all of its critical infrastructures" [17]; "….connecting the physical infrastructure, the IT infrastructure, the social infrastructure, and the business infrastructure to leverage the collective intelligence of the city" [18]; "…combining ICT and Web 2.0 technology with other organizational, design and planning efforts to…. help to identify new, innovative solutions to city management complexity, in order to improve sustainability and livability" [19]; "The use of Smart Computing technologies to make the critical infrastructure components and services of a city… …. more intelligent, interconnected, and efficient" [20].

Thus, *the innovation as the Smart City concept's first key element* is implied in one way or in another in all these five quotations mentioned above. We do accept exactly this idea, because an urban innovation can be implemented only in *a geospatial perspective of the urban space*, while this perspective is being considered in the next section of our paper. In this aspect we define *a Smart City as a comprehensive procedure of innovations within the urban trinity: 1) urban residents, 2) local infrastructural network, both municipal, and commercial, 3) urban processes and phenomenon.*

The Smart City concept's second key element may be selected as *its scalability.* The normal way of the SCC evolution is its moving from some particular projects to some international strategies, through which the city challenges are addressed upon different scales - national, regional, international [21]. These authors, we have just referred to, emphasize: "Thus, it has been observed that it is necessary develop a strategy within city framework to articulate projects in different dimensions in order to achieve a holistic and comprehensive vision". According to this, the *global scale* is the mandatory premise of City balance in *various dimensions*, which only can contribute to the SCC good performance. Without the global goals, the SCC sooner of all performs quite vague projects, which results are not able to be expanded to other scales. Many researches do agree with such conclusion [13, 22-24]. The global or national scales may provide negative impact on urban sustainability and, understandably, on the SCC implementation perspectives, because of the peculiarities of the pollical system in a certain country, as in contemporary Russia [25].

Thus, the cities corresponding to the SCC can be displayed as *the instrumental combination across many urban scales* [26]. These technological and information instruments are connected through multiple networks in a city, and some of these networks can provide continuous data concerning the movements of human and physical capitals. From these flows of initial data, the flow of derivative data is generated, which substantially contributes to the formation of the whole city content. Nonetheless, the cities become smart, only if they provide some intelligence functions. These functions mix, integrate, and combine initial data purposely, finding the ways of enhancing the efficiency, social equity, environmental security, and long-term sustainability of residents' life in smart cities. After all, it is quite understandable, that the Smart City's scalability is also related to its geospatial perspective.

Gathering, measuring, and mining of the spatial urban data can be accepted as *the Smart City concept's third key element.* Flows of people, materials, and energy within urban areas can be automatically sensed for the time being due to the modern information technologies, and the data relevant are generated. This has taken place mainly for three latest decades. These data enhanced by the remote sensing information were normally gathered and displayed with geoinformation tools, firstly with desktop ones, and later on with the processing and visual systems on the web, where various urban maps used for navigation, spatial distribution values, and predicting spatial estimation were the ultimate results [27-32].

While satellite remote sensing pixel images with urban information have been significantly employed for several recent decades, the LiDAR surveying technique gradually becomes the dominant one as *both local, and regional scale sensing*, what can be available with the variety of scanning hardware and point cloud data processing software appeared mainly in two recent decades [33]. An Airborne LIDAR system usually returns a 3D cloud of point measurements from mirrored features scanned by the laser beneath the air-flight route. This three-dimensional cloud with irregular spacing reflects various discrete feature within some AOI (an area of interest). The laser-scanned features normally include *buildings*, other human infrastructure objects, different vegetation belts (canopy and understory), and “bare earth.” To generate a Digital Elevation Model (a DEM), measurements from ground and nonground objects have to be calculated and classified. We can utilize the linear least squares interpolation technique iteratively to remove tree measurements and generate a DEM in urbanized areas.

The key premise of the involvement of the urban remote sensing in general, and the LiDAR surveying technique, in particular, as well as the employment of the geoinformation technology for the contemporary urban studies is conditioned by the fact that the *digital sensors* have become the main source of the initial information for the Smart City’s concept implementation. Modern digital sensors and GIS-technologies for the urban traffic information processing can suggest robust topological model of optimized traffic trajectories, which contribute to the sustainable urban traffic evolution [34-37]. These systematic studies are normally implemented through those gathering, measuring, and mining of the spatial urban data. Moreover, these procedures lie within already mentioned the SCC geospatial perspective too, and put together that third key element of this concept.

The addressing environmental challengers is considered as *the Smart City concept’s fourth key element* within its geospatial perspective, and the last but one in the list introduced in this paper section. Understandably typical challenges are *urban pollution* and *a necessity to pacify the greenhouse effect.* It is a well-known fact, large urban areas consume more, than 75% of energy generated in the world [38]. It is understandable that many studies focused on the urban environmental policy as long ago as few decades before the Smart City concept took its contemporary form. For example, the seminal book “Nature and the City” takes a look back at early nineties discussing the new policy discourse for looking at urban environmental problems within the frameworks of the ecological modernization concept [39]. This monograph highlights the case studies of environmental policy making in two big cities – Toronto and Los Angeles. The important performance of the actual environmental entities, river watersheds, in urban landscapes of both cities are emphasized, and this is only one from many examples of the geospatial perspective involvement. Addressing environmental challengers upon the SCC implementation should be provided in the most possible complex way by combining these (environmental) issues with other ones related to economic and social projects, governance, human issues and living standards [21]. Only this complex and combined outgoing derivative result can be accepted as the fundamental for the elaboration of the Smart City strategy for meeting present and future city problems in various urban dimensions. Alternatively, some authors introduce the category of “Larger Environmental Context”, in which they include different dimensions, almost those ones, which compound various constituents of the derivative result mentioned above – economic, social, cultural, and even geopolitical issues [15, 40, 41].

The interlink between the smart meter information and the geo-sensor information, which is used to achieve knowledge and awareness with respect to human – urban environment interactions, is *the fifth key element of the SCC in the geospatial perspective.* It is the last one in our list, and the whole content of this SCC key element is reasoned by a complicated interlacement of physical and digital technologies with environmental and social phenomena in a city, while derivative information about this interlacement must be sensed, recorded and quantified [42-44]. With drastic increase of smart meter and digital sensors and completion of such entities, like the advanced metering infrastructure and the Internet of Things, a Smart City has to be equipped and covered with different networks of electronic devices. These networks must be sustainable enough with respect to the city social dynamics, and moreover – concerning probable unfavorable environmental events [45, 46].

Various sets and varieties of physical/digital sensors and digital/physical meters within a given urban area are able to contribute to functional configurations of *urban decision support systems (UDSS)* only in case, when these sensors and meters can delineate as effective picture of an urban life as it possible exactly in its *spatiotemporal context* [42, 47-49]. The spatiotemporal context of urban information is that only entity, which actually opens the geospatial perspective of the SCC. Just because of urban population high densities and concentrations in a typical city area, the latter consists of numerous interactions (*human – urban environment*; *human – urban infrastructure*; *urban infrastructure – urban environment*) between urban citizens and their surroundings and produces extremely complicated view of *the human geographical phenomenon* of a given city. An UDSS mentioned above if planned to be involved in the SCC implementation should have an option to register the dynamics of those interaction within different city districts, on different dates, and at different times. Only upon these conditions a complete geospatial perspective can be seen on the base of the empirical urban information gathered from sensor networks.

Thus, we have outlined in this paper section following *five key elements* of the Smart City concept in the geospatial perspective: *Innovations*; *Scalability*; *Data gathering, measuring, and mining*; *Addressing environmental challengers*; *Interlink* *between the smart meter information and the geosensor information*.

In two following sections we, first of all, examine more in details one from three basic assumptions of the "geospatial perspective ⇔ Smart City concept" affiliation - the *urbogeosystem approach*. Then we consider involvement of five key elements delineated in building the city geospatial information space.

The urbogeosystemic approach as a tool for simulating the "smart urban environment" – a core node of the Smart City hierarchy. The author of this paper has already published several texts in the concept of urban geographic systems for few recent years [7, 50-53]. As the key premise of the urbogeosystemic approach the *theory of cities as systems of systems* has been taken, which was introduced as long before as in late seventies of the former century [54]. Once we did outline the category of an urban geographic system as follows. An urbogeosystem (UGS) is "…. an urban system, which… ….not only allows providing all necessary prerequisites for GIS (a geographical information system) involvement in urban studies, but also secures detailed consideration of the most of linkages and relationships within a given area and reveals pure emergent properties…." [7, P. 110].

Although the urbogeosystematic approach has been listed above only as the *second* key assumption of the Smart City concept's implementation within a geospatial perspective, it can be understandably accepted as *the central combining one*, which builds a bridge between the urban remote sensing and outlined above five key elements of the SCC – two other key assumptions. In this way all three ones become linked together, while a real urbogeosystem, that functionates within a certain extent of the geographical space, can be presented by the *urbogeosystemic ontological model (UOM)*. We understand the latter as some kind of *a trinity-tripod*, that strongly relies on support for and on interconnections among all three of its constituents *(urban citizens, municipal infrastructure, urbanistic processes and phenomena), what taken all together provide that sustainable operating of a given city, which can be evaluated as "smart operating" according to several existing criteria*. Moreover, the UOM facilitates to delineate *the core issue of the Smart City concept within its geospatial perspective - a place of the "smart urban environment"* in the whole hierarchy of the series of environments related to a Smart City (Fig. 1).

The author of this paper has outlined the UOM hierarchy based on what was introduced before as "smart city models" in several literature sources [11, 15-17, 26, 55-58]. Really all these models correspond to the "cities as systems of systems" theory, according to which a smart city is a system, that consists of a number of sub-systems. The practical implementation of the SCC can be exactly started from a creation of a simulating model for a certain selected city. This simulating model is based on the urban remote sensing data, in general [59], or on the LiDAR surveying results, in particular [7, 14, 33, 50]. After a city computer model is generated, desirably, according to 3D City GML standards, the structure of the conceptual UOM of an urban geographical system outlined on the figure below is reasonable to be accepted as *the ultimate architectural design* for this model, that simulates a Smart City. If the "smart urban environment" is a core node of this targeted construction of an urbogeosystem as illustrated, then numerous technological, environmental, and socioeconomic solutions made on the way to the SCC implementation, should be oriented to outlined hierarchy of this UOM (see Fig. 1) [51].

All dimensions in one way or in another involved in the initial presentation of the urbogeosystemic approach [50-53] can be delineated in the urbogeosystemic ontological model outlined above: 1) urban remote sensing data; 2) an applicable Human Geography model; 3) digital information processed into the GIS-primitives; 4) the definite geospatial aspects of all interrelated states of urban environment delineated by this ontological model of an urbogeosystem.

In their turn, all five key elements of the SCC within its geospatial perspective can be easily found within the UOM hierarchy too: *innovations* made in the municipal infrastructure will definitely impact urban processes and local residents; *scalability* becomes an almost mandatory issue due to the necessity to provide policy and management through various spatial scales and socioeconomic scopes; *data mining* makes it possible to view the information proceeding from all three pillars (people, processes, city infrastructure) in a whole picture; *environmental challengers* are dominant in few blocks of the UOM hierarchy; and *interlink* among various sources of urban digital information is the only one, which makes this hierarchy to be sustainable one. Summarizing two first sections of our paper, that directly examine the Smart City entity, related urban phenomena, and relevant solutions, it is necessary to complete one more only issue – to attempt to outline *the Smart City category* from the urbogeosystemic approach's point of view. As basic fundamentals for such outline can be selected those generalizing definitions, which from our point of view are the closest ones to our comprehensive frameworks [15,56, 60,61].

Thus, *the Smart City from the point of view of the urgogeosystemic approach is a city, which operates as a system of sub-systems in robust, sustaina-*

ble, and intelligent way. It is a city that possesses a comprehensive commitment to digital technologies, information managerial practice, and public policy. Three supporting pillars for such city are people – its residents, managed urban processes, and infrastructural networks, while the core entity for a whole construction is the “smart urban environment” (see Fig. 1).

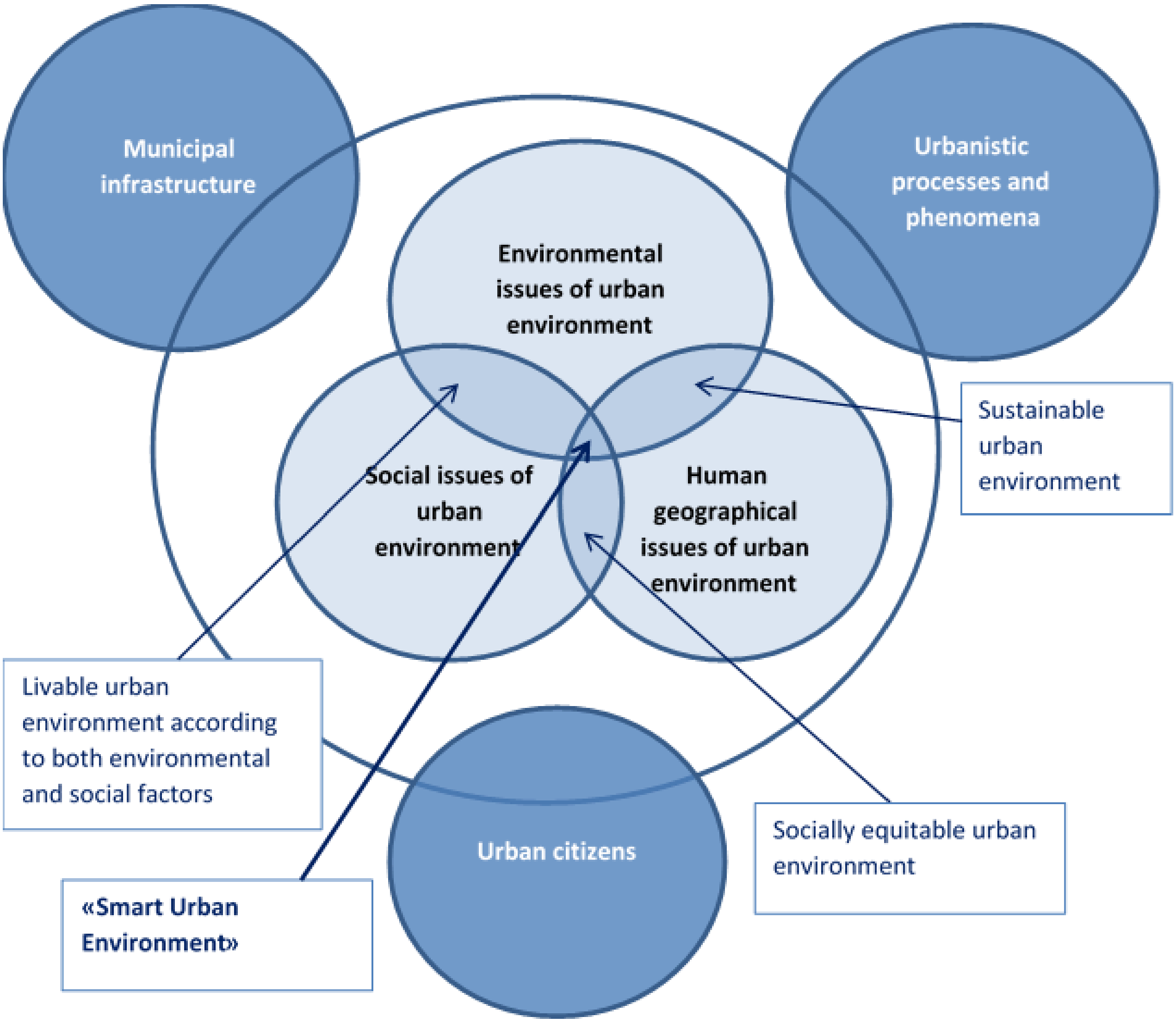


Fig. 1. An ontological model of the UGS with a place of the *smart urban environment”* in the whole hierarchy of the series of environments related to the Smart City [51, P. 110]

Processing results of LiDAR surveying technique. Both Airborne and Terrestrial LiDAR survey have been very demanded in urban environment because of its uniqueness in comparison with other URS results. We have already explained and proved, why *3D city models* obtained from a LiDAR survey through extraction, segmentation, reconstruction, and analysis can hardly be overvalued [7, 62].

Key publications that introduced and discussed similar ideas have been issued for ten-fourteen recent years only [33, 63-67]. The automated building and other man-made feature extraction from LiDAR point clouds together with the relevant topography generation is one of the most challenging research and development goals for city monitoring procedures as well as for support the urban environment by means of informatic software and digital networks. Airborne Laser Surveying (ALS) technique or LIDAR has become quite popular since late nineties, because it provides a fast data collection for a 3D Scene over a massive territory [68].

Contemporary research technique normally combines other data on extracting buildings or uses pre-defined building models, so that the latter would correspond to the roof structures. Surely there are quite a few alternative solutions in the literature to reconstruct the 3D buildings without any supplementary data and predefined roof styles [69]. Also, some attempts were published as long as 15 years ago, that related to use the captured data and convert them into CAD-type models, which would contain walls, roof planes and other building segment planes as well as bare ground which can be promptly visualized from any 3D viewpoint [70].

We have already mentioned above a key subject of LiDAR applications for urban studies – *3D City Models. Besides this the LiDAR surveying technique has been broadly used in many other urban studies, thus becoming a fundamental for the Smart City concept implementation.* In the key existing reviewers on LiDAR survey and its results processing for *urban land cover classification*, five basic domains have been toughly discussed: (1) urban architectural morphology and vegetation analysis, (2) urban flood risk assessment, (3) extracting power transmission lines and other infrastructure, e.g., bridges and roads, (4) modeling GPS/airport signal obstacles, and (5) estimation of solar radiation potential [33, 71].

All LiDAR platforms are either Airborne LiDAR (ALS) – Unmanned Aerial Vehicle (UAV LiDAR), or Terrestrial (Mobile) (MLS) ones. With drastically expanding demand for 3D city models and relevant DEMs, also taking into account increasing availability of ALS / MLS data, 3D building models of robust topology and correct geometry have become the most prominent features of urban environment modeled by LiDAR data processed [14, 33, 50, 62, 65-70, 72, 73]. Evidently, 3D city models as representations of a 3D geometry of urban environment can be obtained from quite various sources [74], but just LiDAR data accepted as the most preferable ones according to the series of understandable reasons. In general, all applied domains of LiDAR surveying techniques may be defined by three following advantages of its approach: 1) High accuracy of the geospatial data collected by LiDAR. Its Point Clouds may illustrate the location of real natural landscape / urban features in a minute details, while an infinitesimal peculiarity may make difference, and it can obscure the whole view of a 3D Scene; 2) Data through an AOI can be collected promptly, and in a costly effective way. Thus, it is possible to hold a quite accurate geospatial monitoring of large areas. This allows to identify urban change detection from multitemporal LiDAR data sets; 3) LiDAR surveying technique provides collection of raw data concerning all the features on the earth surface that belongs to three sets: inanimate nature, vegetation cover, and man-made constructions, buildings, first of all.

Summarizing 1)-3) items that directly relate to the Smart Cities solutions, we should emphasize that the key advantage of the LiDAR technique may lie in that perspective, which allows to build 3D city models within huge territories in an extremely short period of time. Just due to this fact the technology can hardly be overvalued for the *urban planning* industrial area. What is more, correct 3D city models as well as highly accurate DEMs are required for many applications implemented within urban areas including Telecom-issues and wireless communication (the line of sight calculation, optimal allocation of transmitters), emergency response planning, air / noise pollution modelling, municipal infrastructure planning. It is remarkable that all this listed generally coincides with the Smart City necessities reported not only for Western Europe [42, 46], but also for Ukraine [75], as well as for Russia [76].

Our understanding of the LiDAR processing software position in the original illustration with the comprehensive operational *URS / LiDAR / GIS* workflow for the Smart City implementation is defined on Fig. 2. This flowchart directly proceeds from all introduced in our text above.

Urban Remote Sensing for data mining / city analytics and the *EOS LiDAR Tool.* *ELiT (**E**OS **Li**DAR **T**ool)* software is both a separate web-based (network) generator (an engine) – *ELiT Server*, and an integrated component of EOS Platform-as-a-Service software – *ELiT Cloud*, both developed with leading participation of this paper's author [7, 14, 62, 77]. The allied one to these two products is our desktop *ElitCore* software, that possesses even broader functionality. All three mentioned products are the sophisticated solutions based on the complicated algorithms for urban environment modeling and analysis. Two products of this software family normally perform from the Web browser installed on the user's workstation. A series of *ELiT* end user's cases can be applicable with all five *ELIT* key functionalities: *BE – Building Extraction*, *BEF – Building Extraction with Footprint; BERA – Building Extraction Rural Area*, *CD – Change Detection*, *DEM-G - Digital Elevation Model Generation* [Fig. 3]. Some of these use cases are presented in the next section of this paper.

First of all, we have to examine briefly straightforward advantages of using this LiDAR data processing software and to outline what peculiarities would demonstrate any applied Smart City project of real data, that we attempt to complete?

In previous attempts the delivery "urban settlements into smart cities" have been considered, realized, and planned through *several levels* [26, 28, 78], and the scalability procedure mentioned in this text above could be applied then for interchange of the information obtained from various levels. By processing LiDAR data, the *ELiT* software provides huge volumes of information for different applications and reveals several attractive advantages due to applying to these urban levels, over traditional methods for mapping with other remote sensing data. *ELiT* functionalities result from that fact, according to which LiDAR data alter the whole concept of urban mapping and gaining popularity in domains

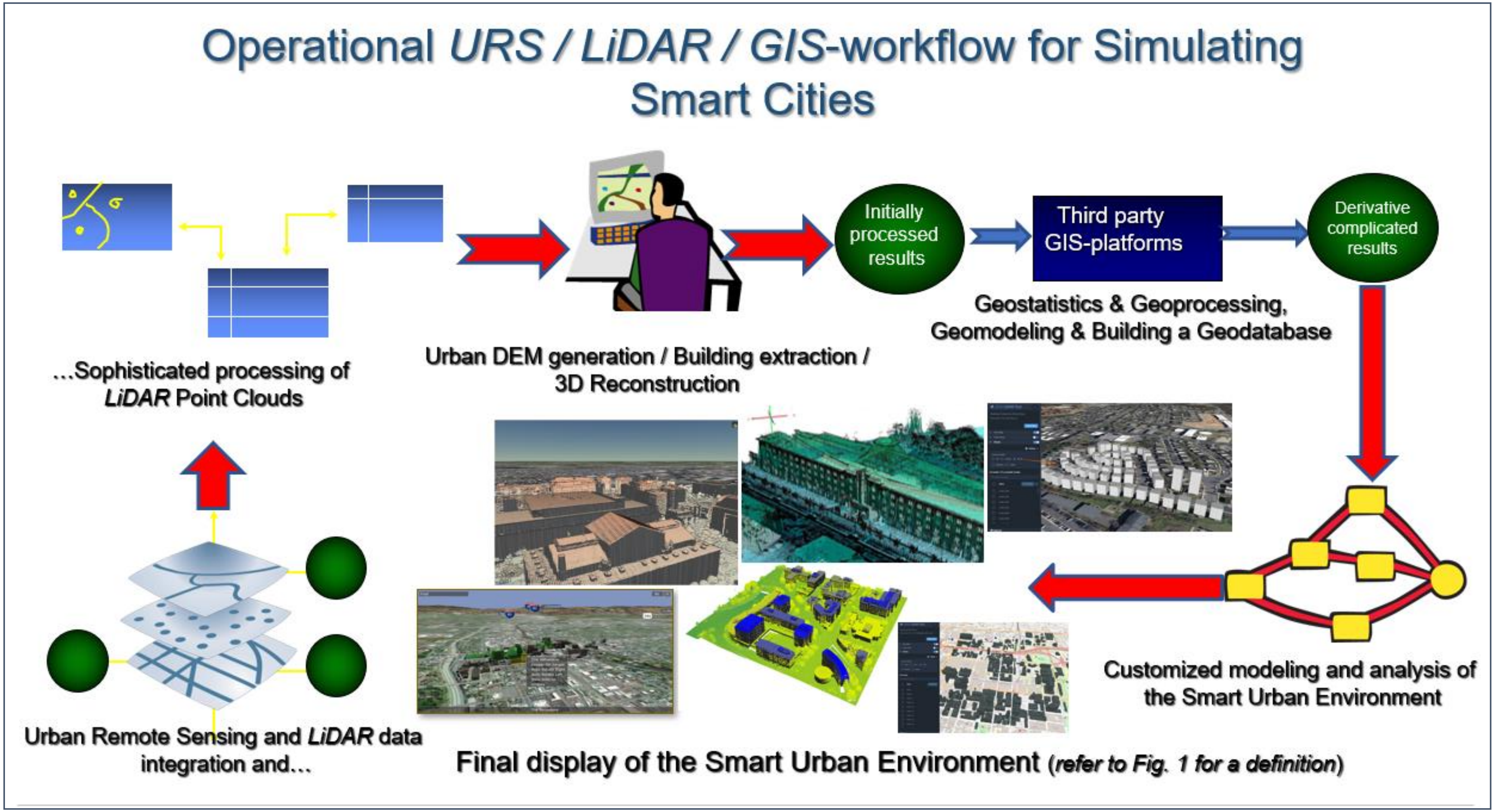


Fig. 2. An operational *URS / LiDAR / GIS*-workflow for simulating Smart Cities with outlining the Smart Urban Environment place in it

such as *heavy urban networking* and *massive data integration*, *pollution monitoring* and *urban land classification*. All these domains can take an advantage of combining LiDAR data and *ELiT* geoinformation functionality to provide analysis and manage, visualize, and disseminate results of *sophisticated processing of LiDAR Point Clouds* as it outlined on Fig. 2. After a block of *3D Reconstruction* a flowchart leads to the unit of *Geomodeling & Building a Geodatabase*.

The *ELiT* multifunctional approach is that key premise, which connects up all these diverse components in the robust geoinformation workflow (refer to Fig. 2). The key output of this workflow, *Final display of the Smart Urban Environment*, is the applied results of a theoretical entity presentation outlined and explained earlier (refer to Fig. 1). In this way, processing results of LiDAR surveys *ELiT* software can relate the infrastructures of smart cities to their optimal planning and further functioning through the urban decision support systems mentioned in this text above in a case, when *ELiT Server* becomes a functional component of such UDSS. Five menus of relevant sub-pages suggest then all necessary calibrated instruments for municipal solutions within three basic classes of the functionalities necessary: *Automated Feature Extraction, Urban Change Detection, Topographic Modeling & Analysis* (refer to Fig. 3).

Despite single known lame summarizing, where one could hardly see any connection between LiDAR and Smart City issues, although it attempts to provide some "direct bridge" from one to another [79], the majority of other "heavyweight" examples, if they are not directly related to the provision of LiDAR results for Smart Cities, but they suggest the definitely relevant solutions in subject areas of: 1) *solid, impervious surface extraction* in urban areas [80, 81], what, as a rule, strongly indicates marginally urbanized landscapes; 2) *quality assessment of urban environment* [33, 82]; 3) *monitoring of city alterations through change detection* [83-86]; 4) *urban feature extraction and 3D reconstruction for city planning*; there is a real "universe" of literature in this area, thus we do not make any relevant number of references in this #4, but refer only to few key ones [33, 62-64, 70, 73, 87-89]; 5) *geoscience applications for urban studies*; processing results of LiDAR scanning equipment can provide uniquely accurate topographic *X, Y,* and *Z* coordinates of the bare ground surface, including large topographic forms [90] what is highly demanded for urban housing development as well as damages from natural hazards (landslides, debris flow, earthquake damages), which can occur in city areas [91-93].

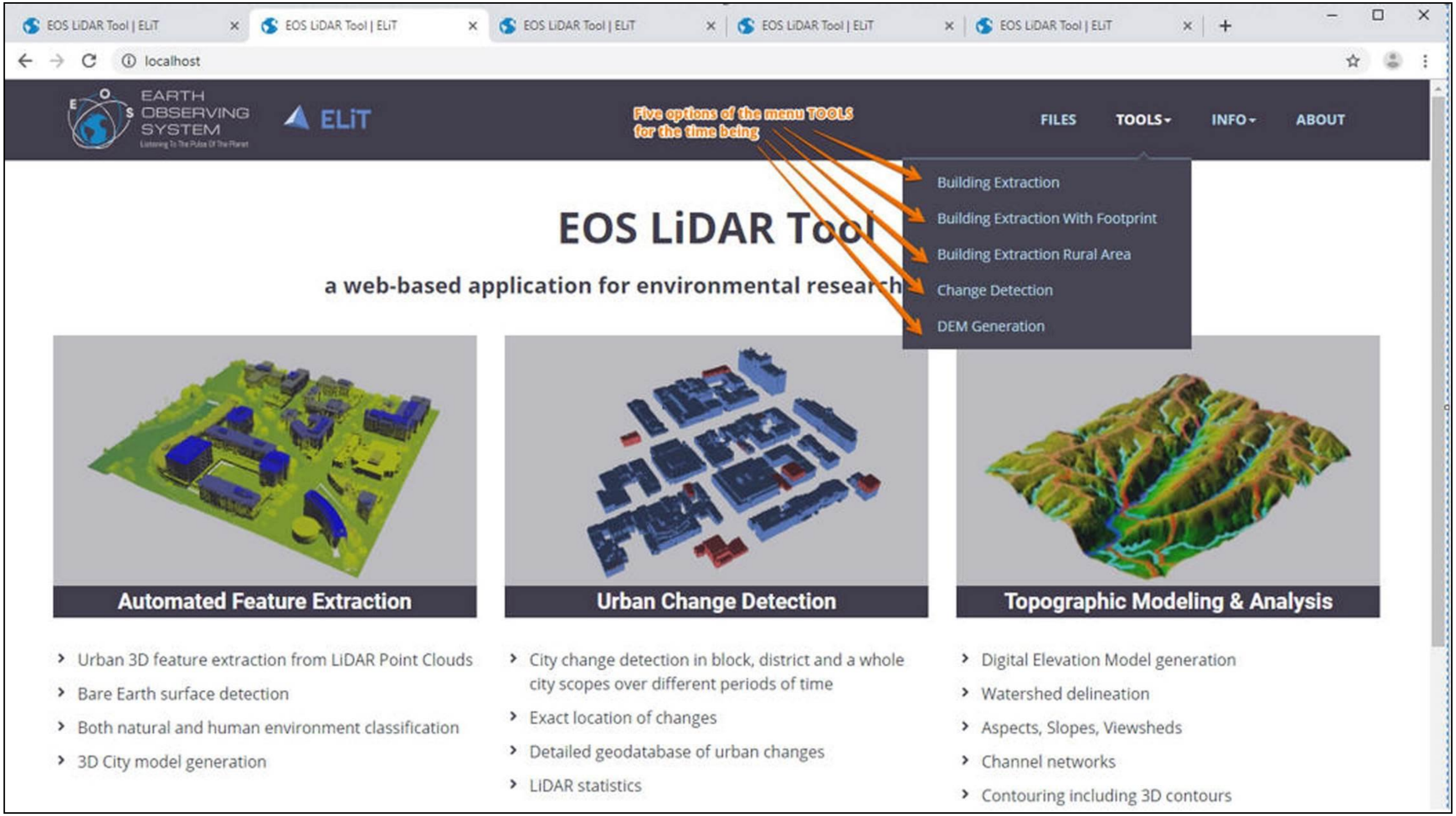
Feasible *ELiT* software use cases for the SCC implementation lie within each of 1)-5) issues and can be provided by all five options of this web-application menu *TOOLS: Building Extraction, Building Extraction with Footprint, Building Extraction Rural Area, Change Detection, DEM Generation* (refer to Fig. 3). According to the mandatory limited volume of this paper we are able to examine only a couple of combined use cases related to *BE / BEF / BERA* functionalities.

The range of Smart City applications dealing with these *ELiT* functionalities is quite long: urban and municipal planning, environmental planning and monitoring, insurance policy and procedures, optimization of sensor placement for technological networks, locational based services, housing development simulations, shadow estimation. In all these use cases a building model can be a primary object of interest. Although the *ELiT* approach does not prescribe any semantics to these models, it is possible such simplified models to interpret city dynamics and networks by examining spatiotemporal changes, and even estimating land use and services distribution in an urban area [94]. Besides these industrial areas we can outline the necessity of building model extraction from Point Cloud *.LAS* due to following reasons:

- to generate complex city mapping products;
- to provide various building renderings;
- to perform advanced three-dimensional modeling as the first step to creating complete and multifunctional digital city models.

Low cost per a surveyed city parcel, functionality of monitoring through a large urban /rural territory promptly and with high level of details are only first few primary advantages of the robust LiDAR pipeline, that necessarily includes the *ELiT* functionalities. Joining of the global mapping coverage (e.g., ESRI imagery, Open Street Maps) with the *ELiT BE / BEF/ BERA / CD / DEM-G* models expedites in easier understanding of the existing urban situation and needs much less resources for interpretation of derivative results, than traditional manual city maps, or even 2D digital cadaster units. Operational decision-making can be completed in a very prompt and cost-effective way within a given urban area with a number of multifunctional *ELiT* 3D city models.

For a few recent years most of the urban data, that can be used for understanding a smart city, have come from the GIS data collecting techniques that include 1) the satellite-enable GPS georeferencing provided for the URS procedures, 2) results of data collecting from technological networks with digital sensors, 3) results of data collecting from dense built-up areas that demonstrate a definite small-scale heterogeneity, 4) data from scanning surveying techniques that differ within a range of a whole city/



EOS LiDAR Tool

a web-based application for environmental research

Automated Feature Extraction

- Urban 3D feature extraction from LiDAR Point Clouds
- Bare Earth surface detection
- Both natural and human environment classification
- 3D City model generation

Urban Change Detection

- City change detection in block, district and a whole city scopes over different periods of time
- Exact location of changes
- Detailed geodatabase of urban changes
- LiDAR statistics

Topographic Modeling & Analysis

- Digital Elevation Model generation
- Watershed delineation
- Aspects, Slopes, Viewsheds
- Channel networks
- Contouring including 3D contours

Fig. 3. The home page of the *ELiT* web-application with five *TOOLS* menu options related to the Smart City simulating procedures (https://eos.com/eos-lidar/)

a city district / a block scopes, and even can focus on minute city parcels, 5) data acquisition from multiple sources of different nature including on-line sensors, 6) completion of 1)-5 issues integration in *the newly geodatabases for Smart Cities*, what would correspond to *Building a Geodatabase block* of an operational *URS / LiDAR / GIS*-workflow (refer to Fig. 2).

URS data mining / city analytics for the Smart Cities, which consists of six relevant to urban data issues delineated above, strongly corresponds to the geospatial perspective of the Smart City concept, in general, and to five key elements of the SCC in the geospatial perspective, in particular. On the base of the following references all six issues delineated for urban data mining can be easily put in compliance with *three key subject areas* examined in our paper: *Data collection, integration*, and *further processing* for the SCC implementation, including spatiotemporal data management and adding data value by integration of the massive data by ICT (Information and Telecommunication Technologies) [26, 60, 95]; *Urban remote sensing*, which generates, first of all, building information, which is used for several applications directly related to the paradigm of the Smart Cities, enhancing routing URS technique by computer vision and socioeconomic approaches [93, 95, 96]; *LiDAR surveying technique* for the "smart urban environment" simulation (refer to Fig. 1) [63-68, 73, 80-93, 98, 99]. The whole framework of the URS data mining also implies the following three steps of each use case development that should take place for any *ELiT* functionality selected for the SCC implementation:

1. Selection of an appropriate functionality for a given project data requirement, taking into account the working environment, in which the given LiDAR dataset are being collected. **2.** Definition of a complete and transparent approach to define uncertainty in urban modeling with respect to modeling error measurements such that the urban planning procedure bankability requirements are met. **3.** Undertaking reliable and transparent comparison of the *ELiT* modeled results with the other information (a municipal cadaster, global maps, etc.) due to city buildings, infrastructures, other assets, and topographic surface.

The *Urban Planning* domain mainly is the disciplinary area of the *strategic* and *long-term* land use planning, which considers several aspects of both natural and human environments for municipalities and communities [100]. The key issue in here is that upon the SCC this subject area becomes much broader and, what is more, it triggers through URS data mining, ICT involvement and digital networks. The municipalities have to obtain an *efficient geoinformation spaces* is a mandatory pre-requisite for planned urban growth and functioning *the system-wide effect* in operations and functions of this urban area. The only possible solution that takes this effect into account is *the join-up urban planning*, which means reliable tracking of this effect even upon the massive data integration [26, P. 491].

The effective method for meeting the coming demands in Smart Cities urban planning and management sectors is to develop *the georeferenced data of LiDAR survey web-based processing application* and *a Web GIS-platform* for the generation of 3D city models. The latter, in their turn, would significantly contribute to simulation of the completely new urban intelligence operations and functions by the modern ICT, that are provided for sustainable functioning of urban territories. Such combination (LiDAR survey + *Web-application*, e.g., *ELiT* + GIS-platform) can be considered as the only tool for modeling and displaying an entity, which we outline as the "Smart Urban Environment".

The *ELiT* software use cases for the Smart Cities. As it has been emphasized above, only use cases related to *BE / BEF / BERA* functionalities can be briefly examined in this text. Georeferencing an urban territory and populating it with exactly allocated 3D city models make it much easier for municipal managers to understand a problem arisen under a way to a Smart City, and enables all city services for its prompt solution by geometric / topologic visualization and analysis of the *ELIT* 3D models. All use cases introduced below are strongly within an operational *URS / LiDAR / GIS*-workflow illustrated above (refer to Fig. 2).

ELiT use case (UC) sample 1 for *common urban planning* may be displayed like follows (Fig. 4). For a given housing area (Washington, D.C., open source data from https://aws.amazon.com/ru/blogs/publicsector/lidar-data-for-washington-dc-is-available-as-an-aws-public-dataset/) our software would assign point objects to *one* definite class from *four* nominated (i.e. *ground*, *vegetation*, *buildings*, *other infrastructure*). Efficient spatial classification as an input secures further applying of thematic feature layers delineation and allows to provide the prompt visual feature analysis "on a fly". Some alternative classes for four mentioned above may be *Buildings, Vegetation, Artificial ground, Natural ground*. Moreover, apart from buildings, there may be in derivative classifications the sets like follows: *Trees, Grassland, Bare soil, Infrastructures*. Thus, it is allowed to state that the *ELiT* representation of an urban area can meet "the overall challenge of integrating contextual information into geospatial analysis for smart cities…" [42, P. 17021], what means combining both technical, and research components in urban planning. As a final output within the frameworks of UC sample 1, a number of geometry definition format files (either *.GLTF*, or *.KML* formats) are produced, where each file represents one separate building extracted.

All this completes a combined *3D* picture of a certain urban area, which can be almost of any size according to city borders upon applying a *scalability procedure*.

Since commonly high-resolution LiDAR data generated from point clouds have been proved to be the most efficient data for automated extraction of buildings in densely built-up parts of an urban territory, then a municipal manager should apply to this data in a broad application variety. Within this common municipal planning use-case for smart cities various combinations of these four thematic layers extracted and classified (*ground, vegetation, buildings, other man-made objects*) become the subjects of other use cases.

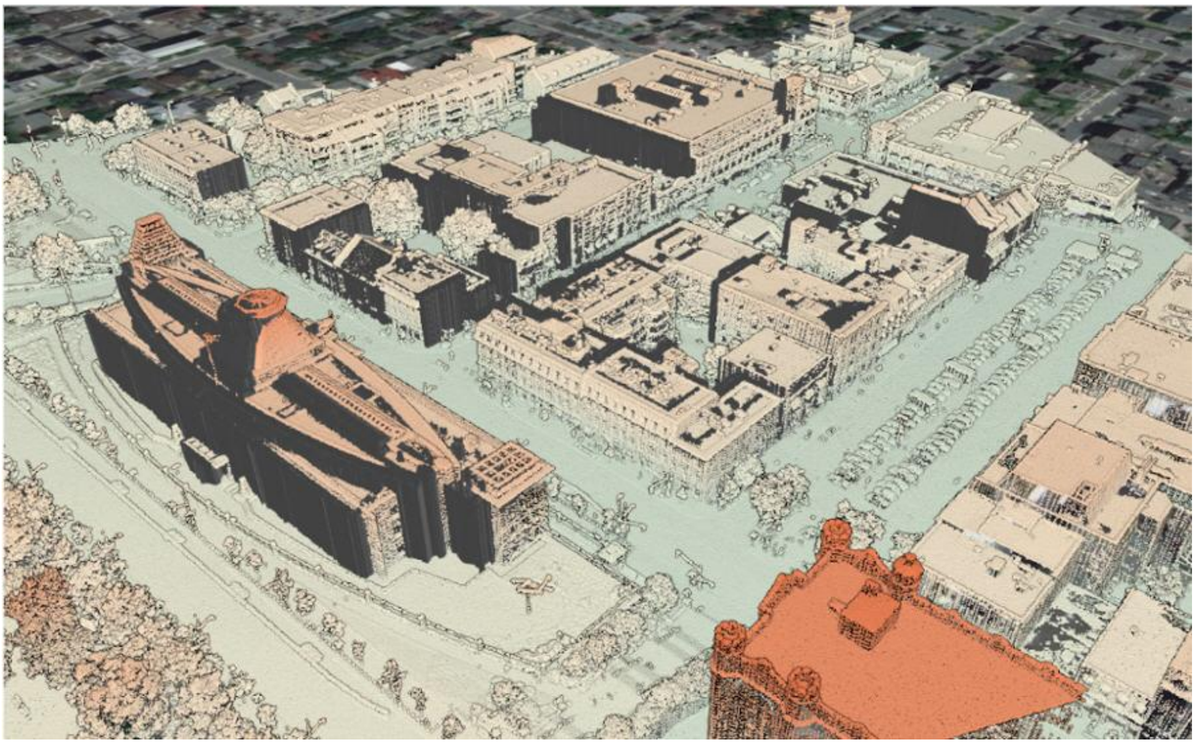


Fig. 4. Displayed results of modeling urban environment within *ELiT UC sample 1*

One of this use cases corresponds to *ELiT UC sample 2* in the same area of common urban planning. This UC provides the *modeled comparison of various urban environments*, what is impossible to complete otherwise than with geoinformation tools (Fig. 5). Using open source LiDAR data from the USGS (the United States Geological Society) website (https://usgs.entwine.io) we have compared with *ELiT* urban areas of four U.S. cities, attempting to make a preliminary estimate how far is each of them from the “smart urban environments”. There is in each of compared units a clear geoinformation context for a new housing or infrastructure development in the area. In this way, it can be visualized for urban planners not just the merits of a new feature allocation, but how it interacts with all other features that already exist.

Obviously, this comparison cannot answer more or less exactly on the question: which from four cities has gone farther on its way to the “smart urban environment”, because this would need a huge processed volume of massive attributive data. Nonetheless, by developing the relevant pattern recognition technique some approximation of such answer “on-fly” can be done even with the existing *ELiT* functionalities. Evidently, this pattern recognition can be substantially enhanced, if it takes into account human-environment-technological interactions, which have been collected using human and technical sensors.

ELiT UC sample 3 seems to be similar to the first one of common urban planning, but focuses on *the urban asset inspection* domain (Fig. 6). For example, this urban asset inventory task should accomplish a team of municipal engineers in Montreal, Canada. These professionals have to find a quite fast and cost-effective approach to estimate the existing state of urban environment and its deviation from a “smart template”, because up to now they have access to an out-of-dated city cadaster only.

This visualization expedites to obtain a view of a combination of the high quality geometric / topological building models with their semantic attributes (refer to Fig. 3). Reaching this goal means the

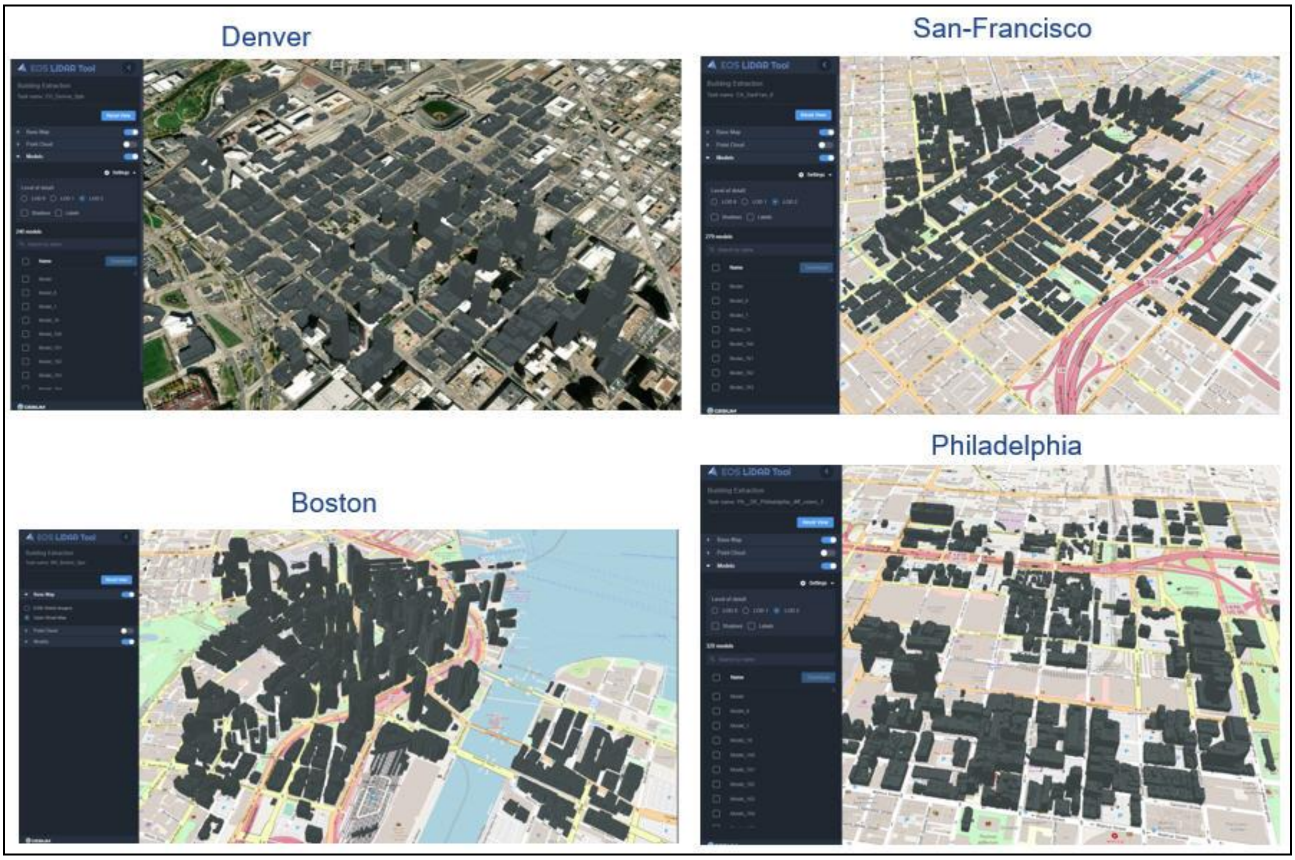
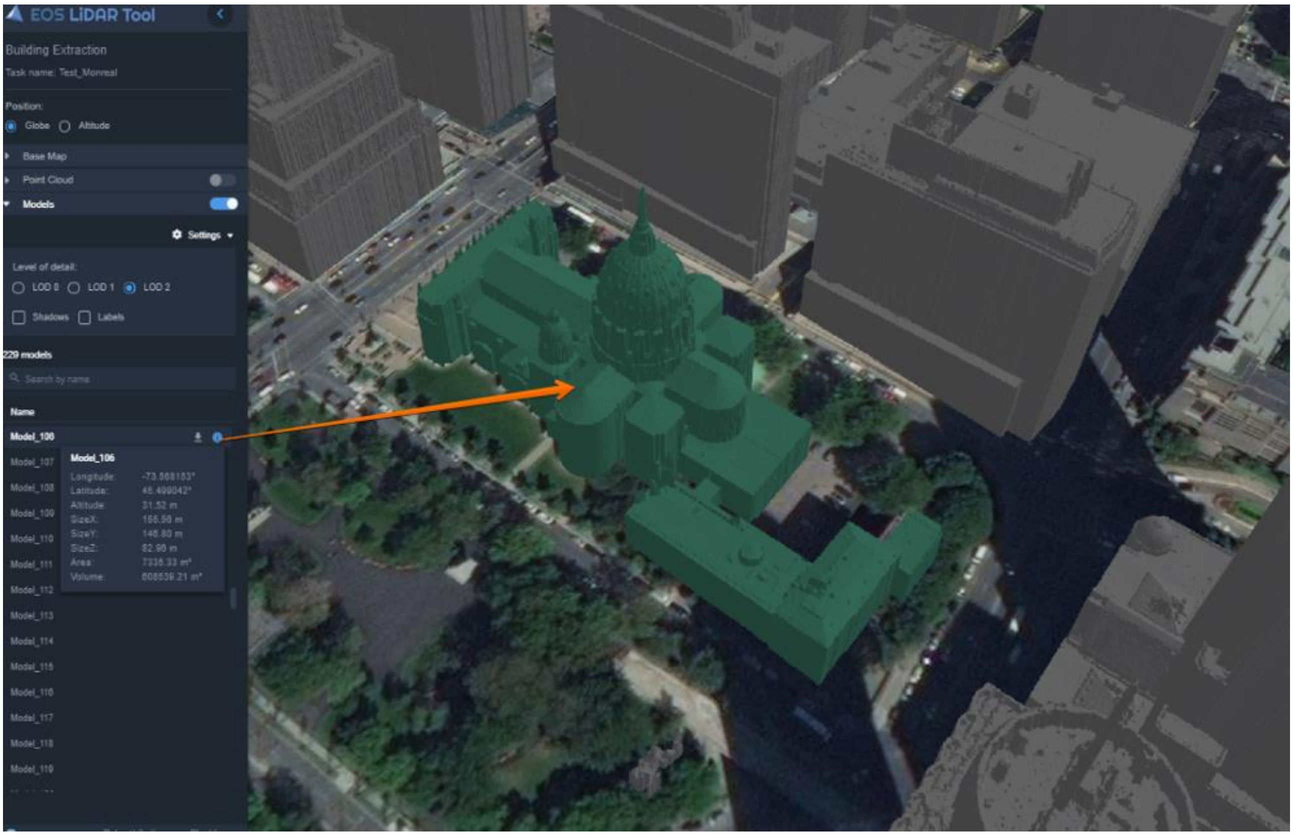


Fig. 5. Displayed results of modeling comparison of four urban environments within *ELiT* UC sample 2



Model_106
Longitude: -73.568153°
Latitude: 45.499042°
Altitude: 31.52 m
SizeX: 155.58 m
SizeY: 146.80 m
SizeZ: 82.96 m
Area: 7338.33 m²
Volume: 608539.21 m³

Fig. 6. A complicated building model with its attributive information within *ELiT UC sample 3*

accomplishment of an urban asset inventory task. This model coupling for the particular AOI helps in better understanding the city situation over a 3D Scene, its already mentioned deviation from "smart template" and does this easier, than with routine 2D paper, or even in comparison with standardized digital maps. Municipal users-practitioners can estimate building locational design, its envelope, and local urban environment for better positioning the perspective housing constructions. What is more, any coming alterations in design and constructions can be estimated, while direct impact on its surroundings of any existing or future building can be evaluated by selecting of any particular model and getting its geometric and semantic attributes (refer to Fig. 6).

A web-visualization is a standard procedure for tourists and investors attraction to a certain city (Fig. 7). In general, the visualization and display of urban environment can be effective for displaying the particular locations of cognate clients, spatial distribution of the market demands for locational-business services, as well as the availability of free space for further housing development as in this *ELiT UC sample 4* (refer to Fig. 7) (Washington, D.C., open source data referred to above). This modeling of urban surroundings can hardly be overvalued taking into account a task of simulating "the Smart Urban Environment", because the latter definitely characterized by complicated social and infrastructural operational configurations and by high population density. This web-modeling and display already presented on illustrations in this paper section actually merge both spatial, and temporal scales of urban environment in this way producing not only maps and scenes for municipal planning purposes, but also – *the spatiotemporal context* [42] for the Smart City concept.

ELiT UC sample 5 directly relates to the *3D City Automated Cadaster*. Many municipalities have been focusing in recent years on developing the real estate registration just in a 3D Cadaster to provide visions of complex property structure, including vertical belongings in buildings to different owners and underground infrastructure (e.g., tunnels, cables, and pipelines, parking lots – Fig. 8).

There are more than one seminal reference in the literature, that understanding the smart city essence is understanding *the structure of topology and geometry of its coupled networks* [26, 42, 44]. If we effectively model technological networks, as it illustrated above, we can bind to these modeled results probable associations of numerous human-environmental-technological interactions that take place in a Smart City area and outline a general geospatial basis, which should be taken as a fundamental for an urban decision support system.

Conclusion, future research and developments. The importance of discussing, how new approaches and techniques in urban remote sensing

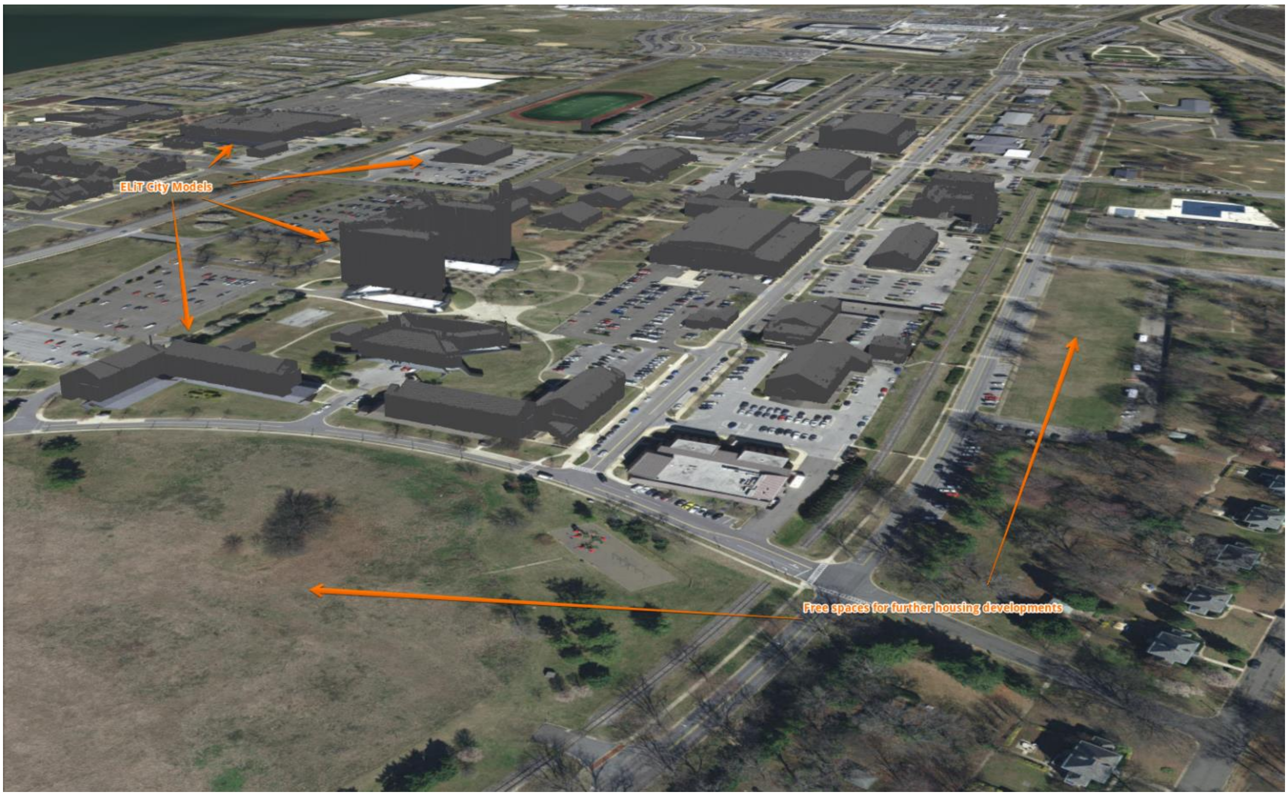


Fig. 7. Modeling and display of urban environment: the detection of free space for the further housing development within *ELiT UC sample 4*

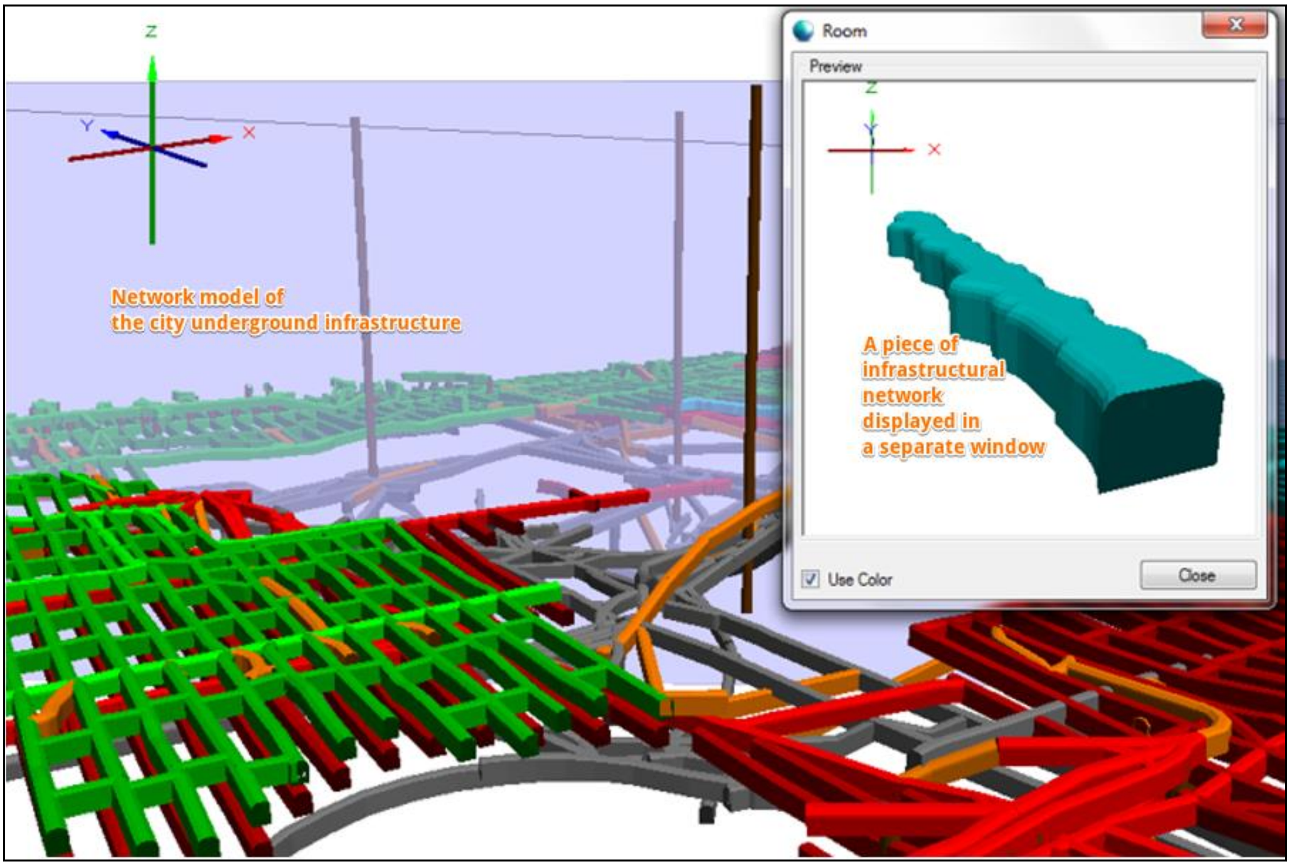


Fig. 8. Modeling and display of underground urban environment with existing infrastructural networks within *ELiT UC sample 5* (the interface of *ElitCore* desktop software)

can contribute to the development of smart cities, is more than evident. In our paper we have attempted to integrate the definitely new ideas within the geospatial perspective of the Smart City concept with LiDAR monitoring and measuring of urban environment and with a number of other relevant procedures within an operational URS / LiDAR / GIS-workflow. The concern remains as to whether or not such integration expedites the Smart City implementation into a real practice. To transform this concern into sustainable awareness we have to summarize those issues outlined in this text above, which contribute to the merits of using Urban Remote Sensing with LiDAR for the development of Smart Cities:

- Three basic assumptions and five critically examined key elements of the Smart City concept within its geospatial perspective have been delineated;
- This geospatial perspective is opened by the spatiotemporal context of urban information, and this circumstance may cause different functional configurations of an UDSS;
- A category of the “Smart Urban Environment” has been introduced within the whole hierarchy of the series of environments in the Smart City’s UGS ontological model, while the urbogeosystemic approach has been proved to be an only tool for delineation of such hierarchy;
- A definition of a Smart City has been done from the point of view of the urbogeosystemic approach;
- Five basic domains of using LiDAR in Urban Remote Sensing have been outlined as well as three key advantages of this approach have been emphasized;
- An operational URS / LiDAR / GIS-workflow has been described within the approach of URS for massive data mining / city analytics;
- Six those relevant to urban data for smart cities issues have been underlined, which strongly correspond to the geospatial perspective of the SCC; these issues have been put into compliance with three key subject areas considered in this paper;
- The whole framework of the URS data mining has been divided for three steps mandatory for any relevant use case development by software tools;
- The functionality and user’s interface of the original family of products for LiDAR data processing and 3D city model generation have been introduced by few descriptions of relevant use cases for Smart Cities.

The further key research and developments may be within the trend of the urban geoinformation space creation, what has been already mentioned in this text earlier. The *ELiT* 3D Geo-Database (GDB) Unit will be a mandatory key component of the urban decision support system, while both are included into the geoinformation space for smart cities. This GDB may be a derivation of the rational database schema. A geodatabase for storing and managing *ELiT* 3D city models stands on the CityGML approach and takes a certain place in a general operational workflow (refer to Fig. 2). A GDB would support geometric, semantic, and thematic properties and attributes, taxonomies and aggregations. Its key feature, the city features, represents spatial, georeferenced, geometric entities. Specialized classes of urban features would include buildings, green areas, infrastructure spaces, transportation networks, streets of different ranks, water bodies, vegetation of different belts. This GDB will be implemented as an independent unit of the UDSS, while another unit of this system will support an option of visualization.

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URBAN REMOTE SENSING WITH LIDAR FOR THE SMART CITY CONCEPT IMPLEMENTATION

Introduction of the problem. The paper emphasizes that the key features of the contemporary urban development have caused a number of challengers, which require the innovative technological introductions in urban studies. The **research goal** of this paper means representing a multifunctional approach, which combines author's urbogeosystem (UGS) theory with the URS (Urban Remote Sensing) technique for LiDAR (Light Detection And Ranging) data processing.

The key elements of the Smart City concept within a geospatial perspective. Three basic assumptions are implied due to the affiliation "a geospatial perspective ⬄ the Smart City concept" (SCC). The five key elements of the SCC have been outlined: Innovations; Scalability; Data gathering, measuring, and mining; Addressing environmental challengers; Interlink between the smart meter information and the geosensor information.

The urbogeosystemic approach as a tool for simulating the "smart urban environment" – a core node of the Smart City hierarchy. The urbogeosystemic ontological model has been introduced as a trinity-tripod (urban citizens, municipal infrastructure, urbanistic processes and phenomena). The "smart urban environment" is a core node of an urbogeosystem.

Processing results of LiDAR surveying technique. With increasing availability of LiDAR data, 3D city models of robust topology and correct geometry have become the most prominent features of the urban environment. Three key advantages of the LiDAR surveying technique have been introduced. The flowchart of the operational *URS / LiDAR / GIS* workflow for the Smart City implementation has been depicted.

Urban Remote Sensing for data mining / city analytics and the *EOS LiDAR Tool.* ELiT *(**E**OS **Li**DAR **T**ool)* software is both a separate web-based (network) generator (an engine) – *ELiT Server*, and an integrated component of EOS Platform-as-a-Service software – *ELiT Cloud*. The allied one to these two products is our desktop *ElitCore* software, that possesses even broader functionality. The paper outlines the whole framework of urban data mining / city analytics relevant to the mentioned applications.

The *ELiT* software use cases for the Smart Cities. A number of use cases that can be completed with the *ELiT* software in the common urban planning domain have been described and illustrated. Each from five scenarios presented suggests some unique solution within the frameworks of the SCC implementation.

Conclusion, future research and developments. The completed research results have been summarized. An entity of the urban geoinformation space has been introduced. A geodatabase of *ELiT* 3D city models has been assigned a mandatory key component of the urban decision support system.

Keywords: LiDAR remote sensing, urban environment, the Smart City concept, interface and functionality of GIS web-application, software use cases, urban decision support system.

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