From GIS to Smart Cities: Key-Concept Landmarks

Robert Laurini
Knowledge Systems Institute, USA
and INSA, University of Lyon, France
Roberto.Laurini@gmail.com

***Abstract* —** From the early beginning of computing, electronic data processing and then information and communication technologies have been used to manage and plan cities. The objective of this paper is to exhibit the key-concepts which have been coined from the stages of Geographic Information Systems until those of Smart Cities. As the main pillars of the GIS period were multimedia data, spatial analysis, geographic database and mapping, for Smart Cities, the pillars appear to be big data, deep learning, knowledge engineering and geovisualization.

***Keywords* —** Geographic information systems, Smart Cities, Cartography, Big Data, Deep Learning, Geographic Knowledge.

I. INTRODUCTION

From centuries, and perhaps millennia, humans were facing the challenges regarding the management of cities and urban planning. Since WW II, with the inception of computing, the landscape is totally different, and moreover some colleagues (Blasi et al., 1968) have coined the expression "Computer-aided urban planning". Figure 1 shows the main books showing the evolution of concepts in GISciences.

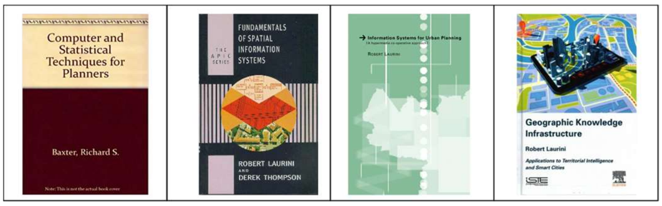

Figure 1. Four books showing the evolution of GIScience concepts.

The goal of this paper is to rapidly sketch the evolution of concepts from the ages of early pioneers in Geographic Information Systems (GIS) to the advent of smart cities. For those interested by the history of GIS, let me advise them to refer to Foresman (1998), Chrisman (2004) or Hoel et al. (2013).

II. EARLY BEGINNING TO GIS

At the beginning of 70s, in France, the main applications were accounting, wages and the registers of electors. Since storage capacities were limited, few have been done regarding urban planning.

2.1 Historic landmarks

But some people, essentially in Harvard begun to think about using computers. At this time, data acquisition was not an easy task (through punched cards) and mapping was made through line printers with some overprinting facilities (Figure 2).

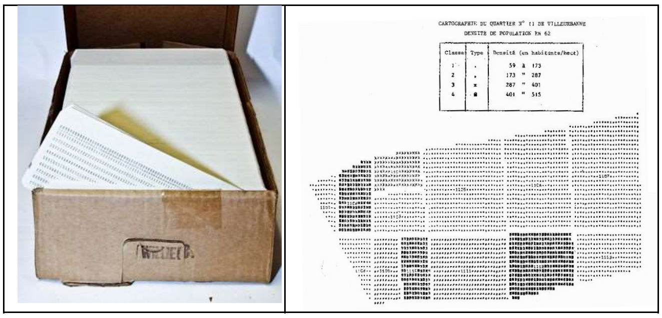

Figure 2. Cards and early computer mapping.

According to ESRI [1] and Chrisman (2004), while at Northwestern University in 1964, Howard Fisher created one of the first computer mapping software programs known as SYMAP. In 1965, he established the Harvard Laboratory for Computer Graphics. In 1969, Jack Dangermond, a member of the Harvard Lab, founded Environmental Systems Research Institute, Inc. (ESRI). The consulting firm applied computer mapping and spatial analysis to help land use planners and land resource managers make informed decisions. In 1980, ESRI created ArcGIS. Now ESRI has 43 % of GIS market worldwide with 3800 employees.

Rapidly, pen plotters were used from 1975 to 2000. Now laser printers are commonly used.

Concerning urban planning, refer to Baxter (1976) (Figure 1).

At this period, urban modeling was very important, i.e. to find mathematical model for urban development. A synthesis was made in 1975 by Baxter et al. (1975).

[1] https://www.esri.com/en-us/what-is-gis/history-of-gis

2.2. Conceptual landmarks

In this paragraph, not all concepts relative to the early ages, but only those which will be used as foundations of the future GIS will be presented. Among them, will be detailed the problem of coordinates, the modeling of polygons, layers, spatial processing and spatial analysis.

2.2.1. Coordinates

Since the beginning, one of the crucial elements was storing coordinates. But what coordinates? The national system for planar mapping generally selected in the middle of the XIXth century or the couple latitude/longitude, sometimes called LATLONG. Under the expression "Computer-aided mapping", it was clear that the role of computer was to change scale and sometimes colors. But rapidly, the LATLONG system was used when it was decided to glue on flat national referencing systems.

When both x (eastings) and y (northings) are access keys, this 2D. When z (height or elevation) is taken as an attribute, the expression 2.5D is used. And when x, y and z are real access-keys, this is really 3D.

2.2.2. Polygons and tessellations

The second problem was storing polygons. Are polygons either ordered sets of points, or sets of segments? With database systems such as CODASYL, both were easily implemented. But the advent of relational systems created by Edgar Codd in 1975, the storing was delicate. That is the reason why other systems were used to store data such as INFO selected by ESRI. Indeed, there exist non-connected polygons; take Italy for instance: this country has several islands and two holes namely Vatican and San Marino. In conclusion, to store a polygon, we need to state the number of connected sub-polygon and state whether they must be added or discarded.

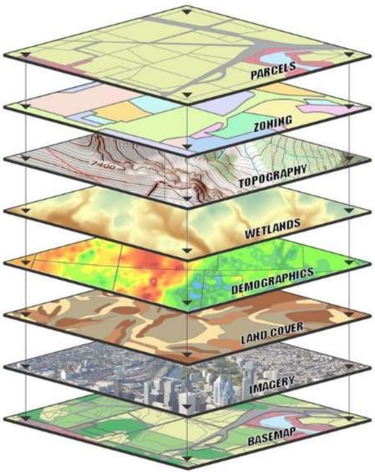

Figure 3. Example of layers. From http://www.co.ontario.ny.us/1176/GIS-Program-Background.

A connected problem was the storing of tessellations since generally polygons are not isolated but are organized into tessellations (cadaster, countries, etc.). To solve this problem, an association named SORSA was created (Segment-oriented Referencing System Association) in order to promote the segment approach for tessellations.

2.2.3. Layers

In a city, there are different sets of data relative to buildings, electricity, sewerages, roads, etc. In order to organize data, the concept of layer was forged, a layer being a set of connected items (Figure 3).

2.2.4. Spatial processing

In order to select a polygon, a key-problem was the so-called point-in-a-polygon problem, so giving inception of several algorithms, the more powerful was the one based on the number of intersections based on Jordan's half-line theorem.

2.2.5. Spatial analysis

By spatial analysis, we mean a set of techniques among which are found, characterization of territories, spatial correlations, interpolation techniques, graph analysis, etc. Often those techniques are linked with visualization. In Figure 4, an example is given regarding for noise study.

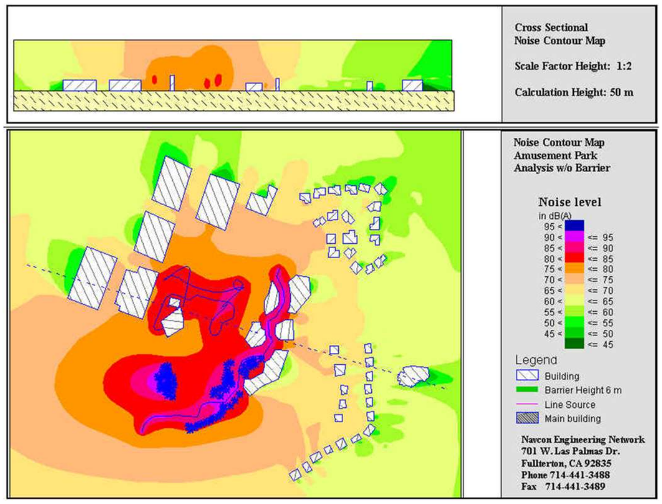

Figure 4. Example for noise study.

2.3. Attainments

In this period, several directions were explored, and some tracks were abandoned. Nevertheless, some issues could be revisited whenever the problem comes again in the critical path of research. However, the foundations of using computers for urban affairs were ready to give birth to geographic information systems.

III. 3 – GIS, DEFINITION, STRUCTURE, MAIN CONCEPTS, APPLICATION

Even as in 1980-85, all GIS components were in place, some additional concepts were emerging, some coming from technology evolution and customer demands.

3.1. Data acquisition

As in the early stages, data were overall coming from digitizing tablets, and other instruments were more and more designed and used such as new theodolites, aerial photos, satellite images, laser data, etc. In other words, the variety of data sources was involving revisiting some concepts.

3.2. Abstract Data Type for Geometry

At the beginning, each GIS maker has its solution to store geographic data. But, when the creation of a new abstract data type, generally named GEOMETRY, the problem was solved to store any kind of geometric shape, points, lines, polygons, etc.,

Finally, the OGC consortium have proposed the following way to store any kind of geometric entity (Figure 5).

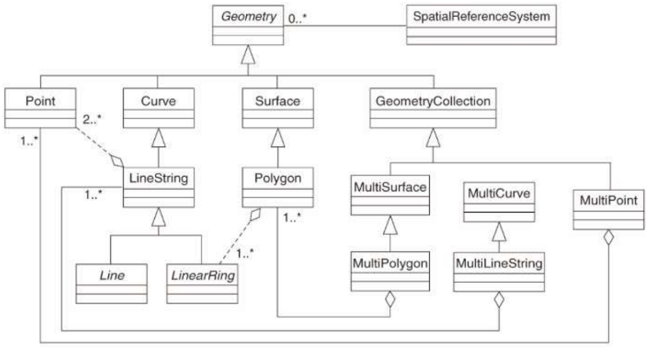

Figure 5. Storing geometry according to OGC.

3.3. The vector-raster debate

Hence, two geometric formats were emerging, the so-called "vector format" for storing lines, polygons and tessellations, and the "raster format" for photos, images and field-oriented data based on small squares (Couclelis, 1992). By field-oriented data, one means data relative to temperature, pression, pollution, etc., covering the whole territory; i.e. we are facing a continuous function, such in any point, there is a value $v = f(x, y)$ or $v = f(x, y, z)$. But since, it is not possible to measure values in all points, methods were designed based on the following argument, storing some important points and defining an interpolation technique to estimate any point. Let us rapidly mentioned grid data, contour levels, TIN's (Triangulated Irregular Networks). Those small squares were regrouped and the most popular was quadtrees (Figure 6) which are a recursive subdivision of squares (Samet, 1989).

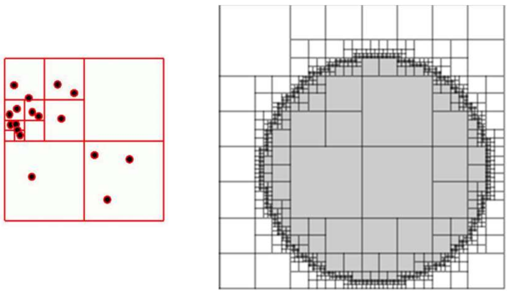

Figure 6. Examples of quadtrees.

Special algorithms were dedicated to both transformations, vector-to-raster which was easy, and raster-to-vector which was considered much more complex.

3.4. Data quality and metadata

In this period, local authorities were owning many datasets from different types and different origins. In other words, quality was considered important. So, the concept of metadata was coined: by metadata, one means data about data, i.e. its origin, its accuracy, its acquisition date, etc. Finally, the following components were exhibited: lineage (origin of data), accuracy, resolution, feature completeness, timeliness, consistency, and metadata quality.

3.5. Indexing

More and more data were stored in databases, and the access time was considered important. In the early GIS, solutions based on rectangular division of spaces were proposed, and also based on space-filling curves such as Peano keys (Figure 7): by bit-interleaving of x and y coordinates, a unique number p can be defined, and so, a linear index can be used as it is done in relational systems. But those indexing methods were out-performed the more popular of which were based on quadtrees, R-trees and variants (Figure 8). See Kothuri et al. 2002).

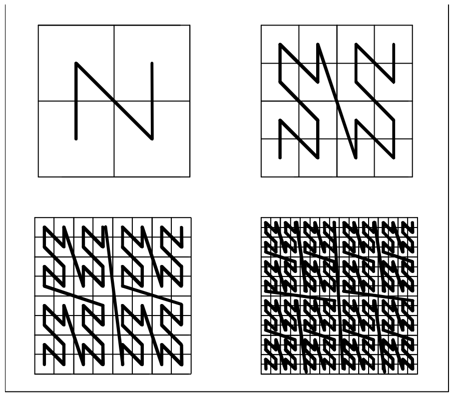

Figure 7. First steps of the N-Peano space-filling curve.

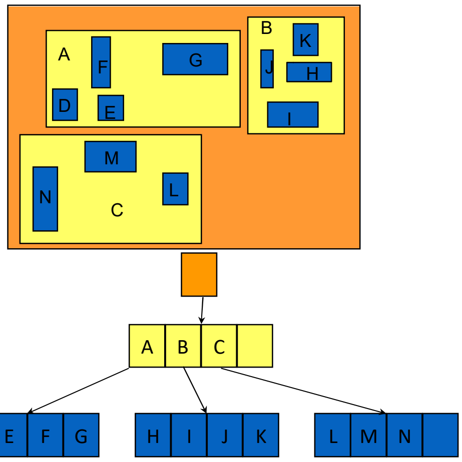

Figure 8. Example of R-tree.

3.6. Topology

The next set of problems was linked to other spatial queries. In addition to the point-in-a-polygon query, computational geometry was used to solve queries such as region queries, intersection, overlay, etc.

But the main problem was in topology. Finally, Egenhofer (final paper in 1994) proposed his set of topological relations (Figure 9) more or less in parallel with the work of Randal et al., the so-called RCC model (1992).

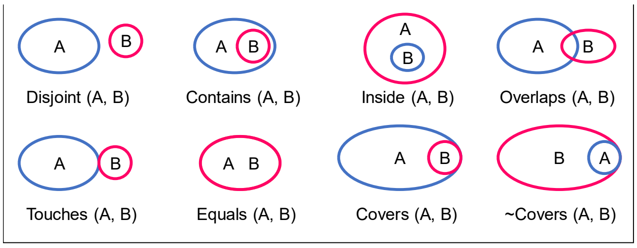

Figure 9. Egenhofer's topological relations.

3.7. Interoperability

Cooperation between local authorities and companies implies the simultaneous usage of several GIS built on different software products and having different formats. The concept of interoperability was incepted to allow different GIS to cooperate. A neighboring concept was federated GIS. It became obvious that, beyond the software problems, two key-problems were identified (Laurini,1998):

- the discrepancy at borders, named cross-border interoperability;
- the discrepancy between data definitions which leads to the creation of geographic ontologies.

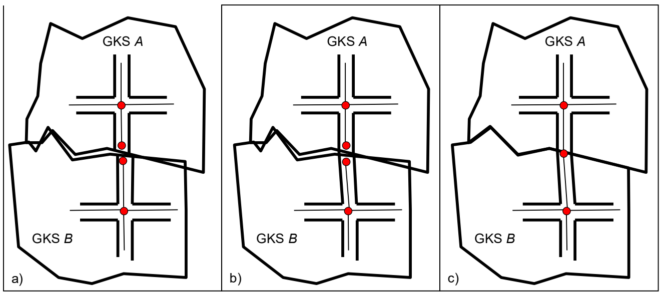

Figure 10. Cross-border discrepancies.

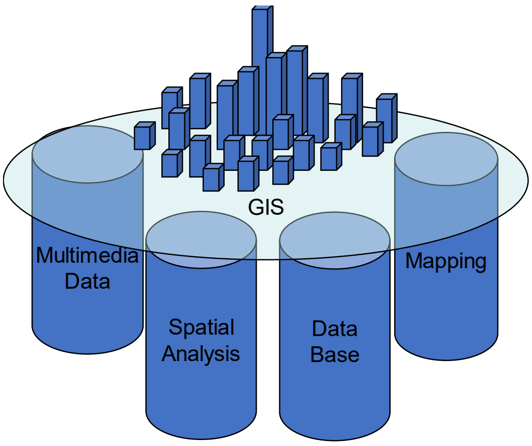

Figure 10. The four pillars of GIS.

Eventually, three levels of continuity can be identified:

- **Geometric continuity:** in which maps look good by correcting border discrepancies so that maps are extended to the neighboring crown; but objects are not reconstructed in the knowledge base (Figure 10a);
- **Semantic continuity:** reconstruction of geographic objects partly cut by borders such as buildings, parcels, etc. (Figure 10a);
- **Topological continuity for networks:** this will allow consistent graph reasoning (Figure 10a).

3.8. Four pillars of GIS

Finally, we can consider that mainstream GIS were based on 4 pillars, namely multimedia data, databases, mapping and spatial analysis (Figure 10).

IV. SMART CITIES

The evolution of IC technologies and demands of customers have changed the panorama. Now, the concept of Smart City allows us to completely revisit urban planning and city management. Several definitions can be provided, all taking into account ICT to govern a city at various levels involving smart citizens and smart governance such as in the Mathew's diamond (Figure 11). Similarly, four ICT pillars can be exhibited, realtime massive data, deep learning, knowledge engineering and geovisualization.

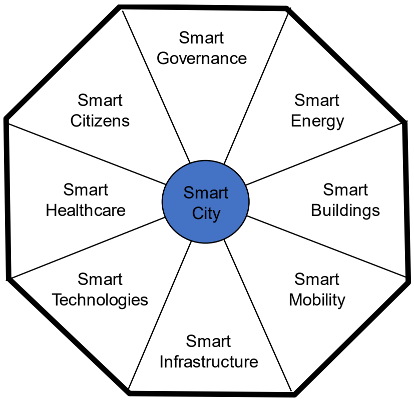

Figure 11. The Smart City diamond according to Mathew (2013).

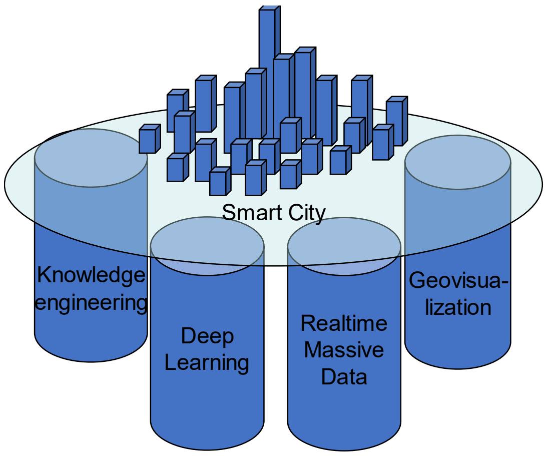

Figure 12. The four ICT pillars of Smart Cities.

4.1. Realtime Massive Data

Let us rapidly detail some components, sensors, IoT and analytics.

4.1.1. Sensors

Now sensors are mainstream. Any lamppost in a city can also integrate a sensor for pollution. For less than 10 euros, you can buy sensors for sound, vibration, fluid velocity, distance, speed, acceleration, light, imaging, pressure, temperature, presence, etc. All of them not only can regularly measure any phenomenon and transmit information, but also have some storage capacity.

Moreover, positioning systems even if they are not really sensors, they have a paramount importance, such as

- Global Positioning System – US military system, fully operational since 1995.
- GLONASS – Russian military system, fully operational since October 2011.
- Galileo – a European system, expected completion is 2019.

Moreover, indoor positioning is also possible likely based on WIFI systems.

Among sensors, let us also mention the importance of drones equipped with GPS and with several sensors.

4.1.2. City-wide IoT

In home automation, Internet of Objects, based on sensors and telecommunication is increasing. Likewise, in a city, the same structure can be developed for instance to command traffic lights, to irrigate some green spaces, etc.

In his presentation about the use of IoT for the Metropolis of Lyon, France, Gastaud (2017) details three applications.

- The first one is the irrigation of trees: indeed, based on sensors put in branches, it is possible to estimate the quantity of water they need, this water coming especially from a repository of rain water. Figure 13 depicts the structure along the Garibaldi Street.
- The second one is the management of bottle banks; sensors measure continuously the level of waste bottles so that to optimize collecting tours.
- The third is energy management in a new development in Lyon, called Confluence.

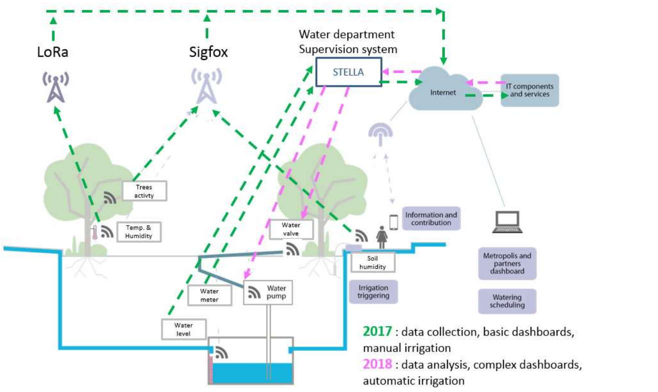

Figure 13. Structure of the tree watering system in Garibaldi Street (Gastaud 2017).

In addition, human can also be considered as sensors, voluntarily or involuntarily (Goodchild, 2007).

4.1.3 Urban Big Data Analytics

Each day, sensors are sending zillions of data. More exactly, according to Shokoohi-Yekta (2018), 90% of the world's data today have been created in the past 2 years.

Big data are usually defined through four characteristics, named the 4 V's, Volume, Variety, Velocity and Veracity.

The problem is not only to store this mass of data and to clean them, but also to identify patterns, to extract knowledge which can be of interest for predictive analytics and user behavior analytics. And these objectives can meet some aspects in urban planning (Batty, 2013), (Al Nuaimi, et al., 2015).

This is the role of data mining to do these tasks. Taking into account geometry, some spatial data mining techniques have been designed and implemented in which co-location is one of the key-concept. See (Shekhar-Zhang, 2006).

4.2. Deep learning

Deep learning is a key-element now in artificial intelligence. Deep learning in broader terms refer to training a system capable of learning and imitating human behavior. It works with large volumes of data (both structured and unstructured) and uses complex algorithms to train a model. Neural networks help implement deep learning.

Remember that an artificial neural network mostly consists of 3 layers (input, hidden and output) and each layer consists of neuron/nodes that perform numerical computations and other operations. Each node in a layer is inter-connected to other nodes present in consecutive layers. There are weights assigned to each interconnection and a bias assigned to each layer. These weights and biases are called parameters of the network. An example of neural network is given in Figure 14.

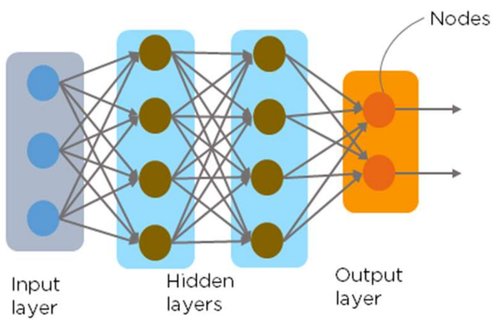

Figure 14. Example of a simple neural network.

For deep learning, there are several layers and each node or neuron is connected to several other nodes. The input layer in the network is responsible for receiving large volumes of data as inputs in different formats (text, files, images, etc.). The hidden layers are where all the calculation, computation and feature extraction take place. The output layer is responsible for generating the desired output.

In other words:

- Neural networks, a beautiful biologically-inspired programming paradigm which enables a computer to learn from observational data; and
- Deep learning, a powerful set of techniques for learning in neural networks.

At the moment being, there is a limited number of applications in urban planning. Anyway, let us mention applications for studying urban morphology (Moosavi, 2017), for video-analytics (Wang-Sng, 2015) or for pavement analysis (Gopalakrishnan, 2018).

4.3. Urban knowledge engineering

One aspect of artificial intelligence is knowledge engineering in which knowledge is often defined by means of rules (`IF-THEN`-rules). But the use of those rules implies to revisit the way urban data are modeled. In (Laurini, 2017), I have proposed to organize knowledge base systems according to the structure as depicted in Figure 15, including geographic objects, relations, structures, ontologies, rules, physico-mathematical models, gazetteers and external knowledge. Let us examine rapidly all of them.

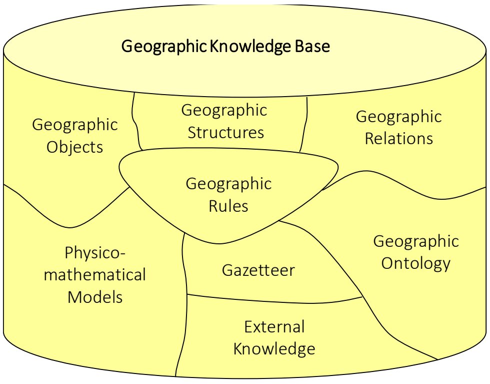

Figure 15. Components of a geographic knowledge base.

4.3.1. Geographic objects

For all geographic features, their models have three components, geometry, semantics and identification. Identification is made through a gazetteer and semantics, an ontology (Figure 16).

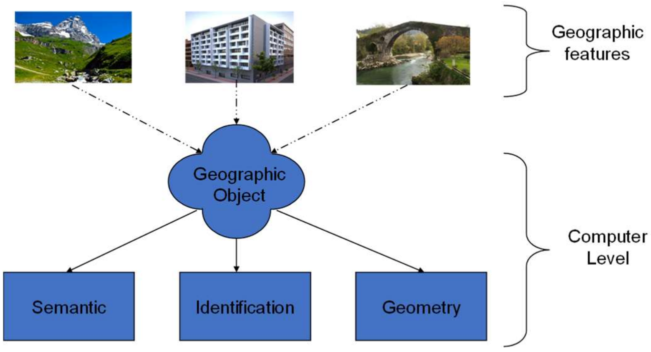

Figure 16. Modeling geographic objects.

In order to allow more flexibility, essentially due to the various way of storing geometry according to scales (a road can be a line, an area or a volume), I have proposed the concept of ribbon which is a line with a width.

4.3.2. Geographic relations

In addition to topological relations, some others are encountered in urban spaces. Let us mention underneath or above (for engineering networks, rivers, tunnel), roads and city-blocks, etc. The majority of those relations defines relationships between networks and spaces.

4.3.3. Geographic ontologies

An ontology can be defined as a semantic networks of object classes and attributes. In geographic ontologies, in addition, some spatial relations can be used. Figure 17 is an excerpt of a road ontology from the Towntology project (Keita et al. 2004). Another example in urban policy planning is given Figure 18 (Teller 2007).

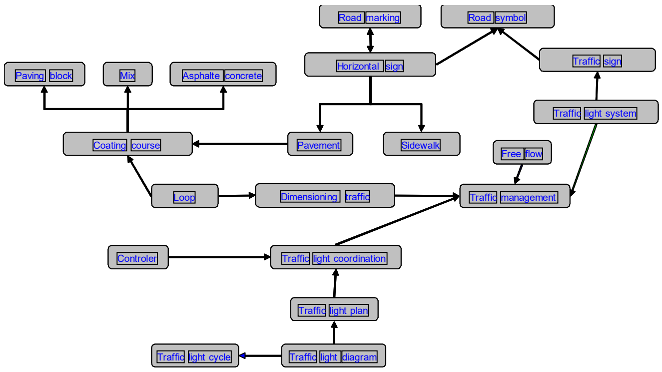

Figure 17. Excerpt of a road ontology in the Towntology project.

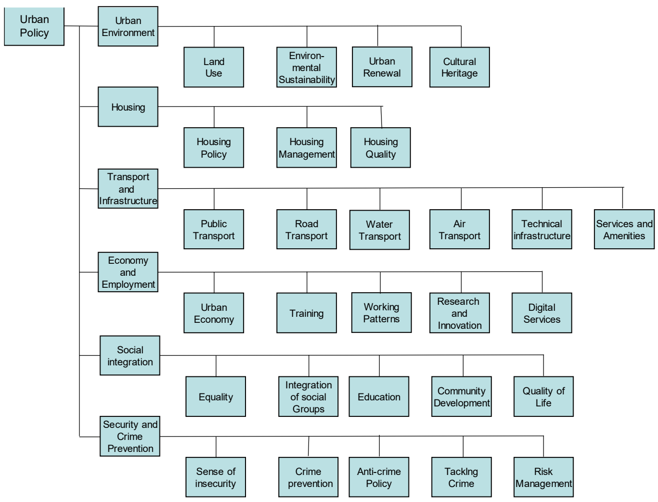

Figure 18. An ontology for urban policy. The European Urban Knowledge Network (EUKN) top-level ontology. The thesaurus is composed of 254 concepts organized into five levels. Quoted by (Teller 2007).

4.3.4. Gazetteers

Originally, a gazetteer was a list of placenames. But now, this is a database including variants of placenames together with their types, possibly in different languages.

4.3.5 Geographic structures

For instance, an airport can include a terminal, a car-park, a landing tracks and some technical building. In other words, the components of an airport are defined by an ontology. Similarly, airports, allotments, campuses, barracks are geographic structures defined through an ontology.

4.3.6. Physico-mathematical models

In the past, many mathematical models have been written for instance in hydrology, in pollution, etc. The idea is not to rewrite those models, but to integrate them into a knowledge base by encapsulation.

4.3.7. Geographic rules

According to (Morgan 2008) and (Ross 2011), rules must be considered as first-class citizens in information technology. In urban planning, many rules can be encountered, for instance:

- If a lane is narrow, make it one-way, except if it is a cul-de-sac (dead end);
- When planning a metro, move underground networks;
- Each building must be connected to utility networks (water, electricity, gas, telephone, internet, etc.);
- Council flats must be connected to urban heating systems;
- If a cross-road is dangerous, install traffic lights;
- In city centers, transform streets into pedestrian precincts;
- When a commercial mall is planned in the vicinity of a city, shops located in the city center will be in jeopardy;
- If the number of car parking lots is insufficient, encourage using buses or bikes;
- At the vicinity of an airport, limit building heights.

As example in urban planning, let us consider the case of somebody having a project to construct a new building within the conservation area of a listed monument. Practically, in all countries, such new construction is prohibited (Figure 19).

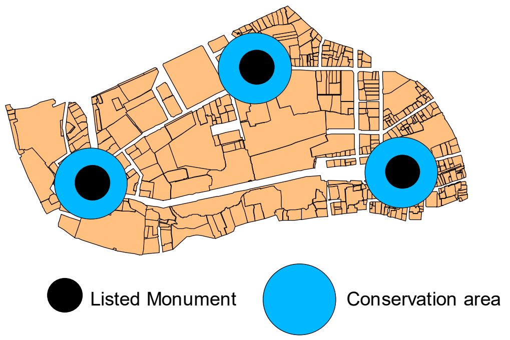

Figure 19. At the vicinity of listed monuments, it is prohibited to construct a new building within the conservation area.

To deny the approbation of this building, the rule can be encoded as follows (distance equals 100 meters), by using the mathematical formalism: *definitions* : *Boolean conditions* ⇒ *consequents*.

$$\forall\ Terr \in EARTH, \forall\ B \in PROJECT, \forall\ M \in GO,$$
$$Type\ (B) = \text{“Building”},$$
$$Type\ (M) = \text{“Listed\_Monument”}:$$
$$Inside\ (Geom\ (B), Terr)$$
$$\wedge\ Inside\ (Geom\ (M), Terr)$$
$$\wedge\ Inside\ (Geom\ (B), Union\ (Buffer\ (Geom\ (M), 100)))$$
$$\Rightarrow$$
$$State\ (B) = \text{“LM\_Denied”}$$

In which

- *Terr,* represents the territory onto which this rule applies,
- *PROJECT*, the set of projects,
- *GO,* the set of geographic objects,
- *M,* an existing monument,
- *B,* a projected building,
- *Inside*, a topological relation,
- *Union* and *Buffer*, geometric functions.

In addition to `IF-THEN`-Fact and `IF-THEN`-Action conventional rules in business intelligence, for us, by taking geometry into account, several other types can be identified:

- *Co-location rules: “if something here, then another thing nearby”*
- *IF-THEN-Zone: for the creation of a zone*
- *Metarule: “IF some conditions hold, THEN apply RuleA”*
- *Located rule: “IF in a place B, THEN apply RuleB”;*
- *Bi-location rule (butterfly effect): “IF something holds in place P, THEN something else in place Q”*

4.3.8. External knowledge

However, it is common that features located outside the jurisdiction of the knowledge base’s owner, can have an important influence (Figure 20): take for instance sea which is usually outside the jurisdiction of a harbor, or a big plant employing many workers outside the city (Laurini and Favetta, (2017).

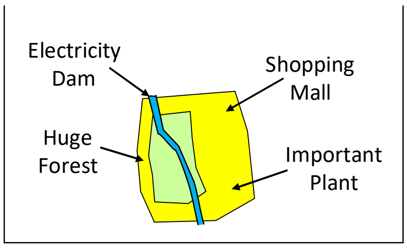

Figure 20. A city is depicted in green, and its neighboring crown in yellow in which there are important features.

Since those features can greatly influence urban reasoning, it is important to include them into the knowledge base.

So, let’s define external knowledge as bunches of knowledge concerning external influences important for a territory. Two categories will be examined:

- Short distance or neighboring knowledge, i.e. knowledge located at the vicinity of the jurisdiction; a solution can be to determine of out-buffer zone around the jurisdiction and consider knowledge inside this buffer zone.
- Long distance knowledge includes the source and contents of external influences including urban technology watching.

4.4. Geovisualization

By geovisualization (short for Geographic Visualization, one refers to a set of tools and techniques supporting the analysis of geographic (so urban) data through the use of interactive visualization (McEachren and Kraak 1997). Beyond conventional cartography, four directions seem of interest, cartograms, 3D visualization, chorems and city-dashboard.

To summarize, geovisualization is an interesting and useful field of research for different reasons:

- It can reduce the time to search information, and support decision-making,
- It can enhance the recognition of patterns, relations, trends and critical points etc.
- It can give a global vision of a situation, a phenomenon, etc.
- It enables the use of human visual memory and the capability of perceptual processing of data,
- It permits a better interaction between user and the information system.
- And it can possibly lead to the discovery of new bunches of knowledge.

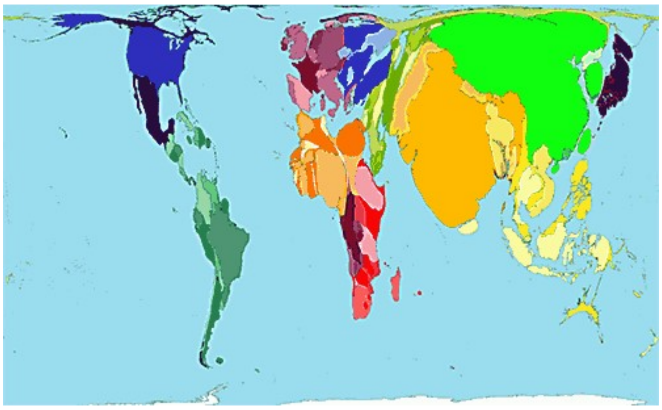

Figure 21. Cartogram of the world population in which the area of each county is proportional to its population.

Figure 22. Cartogram of New-York City. Source http://www.viewsoftheworld.net/?p=2071

4.4.1. Cartograms

Cartograms are a first attempt to produce new maps in which territories are not represented in proportion of their areas but according to another variable. For example, Figure 21 represents the world population in which country's areas are proportional to population and Figure 22 represents the population of New-York City.

4.4.2. 3D visualization

More and more, 3D modeling is used, really in 3D (Figure 23) but also in perspective such as datascapes (Figure 24)

Figure 23. Example of 3D mapping (Autodesk).

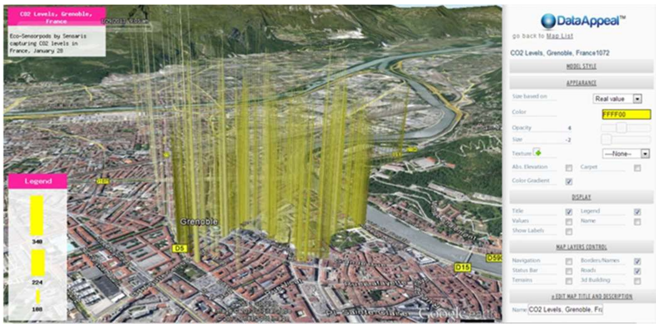

Figure 24. DataAppeal Application showcasing datascape of CO_2 Levels, in Grenoble, France, rendered in light yellow spiky model. From http://archinect.com/features/article/71075299/working-out-of-the-box-nadia-amoroso.

4.4.3. Chorems

Chorems were created in 1980 by Pr. Roger Brunet, a French geographer as a schematic representation of a territory. This word comes from the Greek χώρα which means space, territory. It is not a raw simplification of the reality, but rather aims at representing the whole complexity with simple geometric shapes. Even if it looks a simplification, the chorem tries to represent the structure and the evolution of a territory with a rigorous manner. See an example for New-York City in Figure 25.

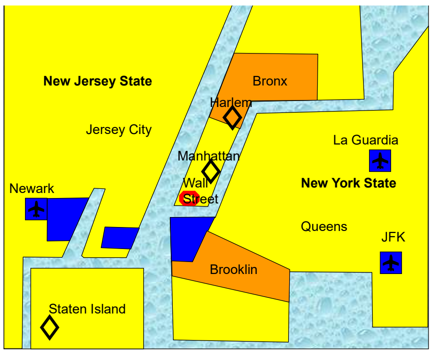

Figure 25. Example of a chorematic representation of New-York City) Translated from https://cahiersdhistoire.net/varia/archives-cartographiques/schema-de-la-ville-de-new-york/

During decades, chorems were designed manually by geographers or experts. Now, they can derive from spatial data mining. For more details, refer to (De Chiara et al. 2012).

In Figure 26, an example is provided presenting migration flows in Tunisia (Cherni et al. 2013). However, to demonstrate that chorems can be generated in real time, an example is given Figure 27 (Bouattou et al. 2017) concerning meteorology in Algeria.

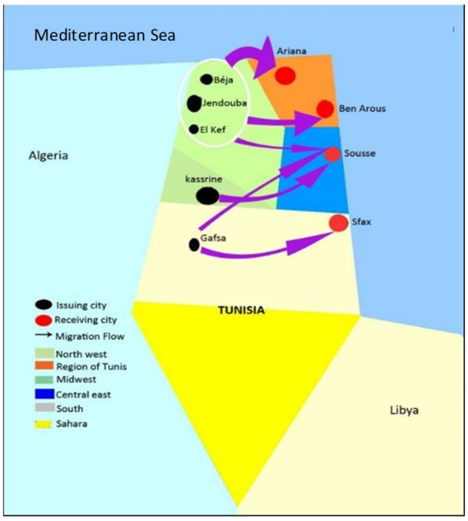

Figure 26. Example of a chorem describing migratory flows in Tunisia (Cherni et al., 2013).

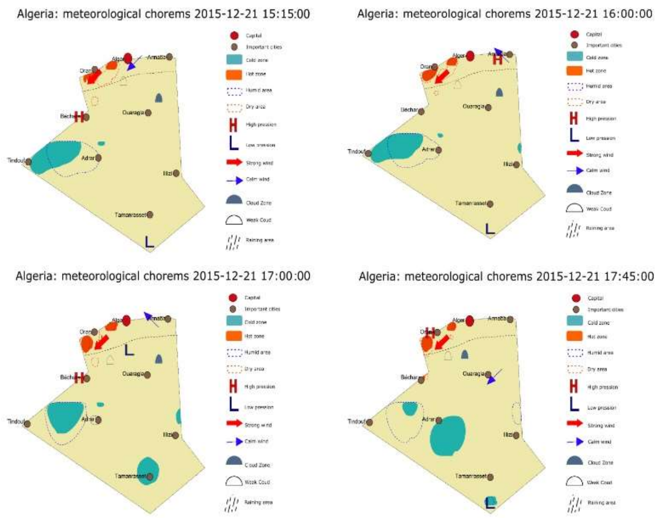

Figure 27. Example of animated chorem in real time for meteorology in Algeria (Bouattou et al. 2017).

4.4.4. Dashboard

Visualization and especially geovisualization on-the-fly and in real time are very for the governance of smart cities and smart territories based on data coming from sensor networks. Applications can be found for traffic management, pollution control, meteorology, disaster management, etc. Two types of dashboards can be considered:

- Multi-thematic dashboards, i.e. in which several indicators are shown simultaneously, maybe thousands on maps (see an example in Figure 28) for the bottle bank example in Lyon;
- Chorem-based dashboards, i.e. in which only the salient aspects, usually named hotspots are recognized and laid-out.

Only the second will be rapidly described based on the Ben Shneiderman's mantra (1997, overview, zoom-and-filter-details on demands). In the overview step, all salient aspects discovered in real time are shown. Then the step zooming-and-filter step will gradually lead the user to the details relative to the concerned hotspots.

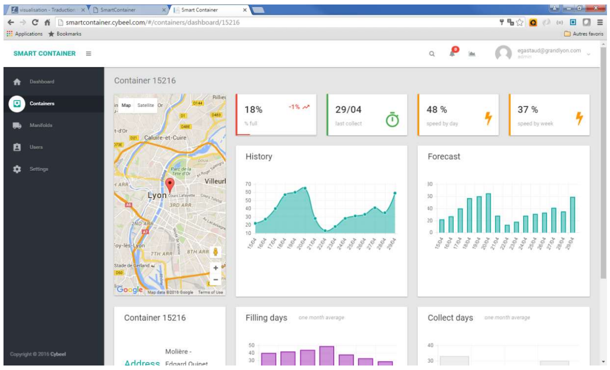

Figure 28. Example of a bottle banks dashboard in the Metropolis of Lyon.

V. Conclusions

The objective was to rapidly sketch the evolution and the main concepts relative to GIS and Smart Cities. As the four GIS pillars were multimedia data, databases, mapping and spatial analysis, it appears that the four ICT pillars of Smart Cities seem, at first glimpse, realtime massive data, deep learning, knowledge engineering and geovisualization. Maybe in the coming decades, other key-concepts must lay in the foundations of Smart Cities.

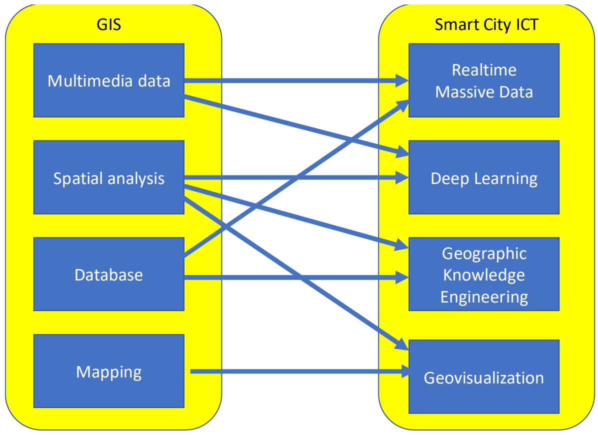

Figure 29. Main links between pillars showing the evolution of key-concepts used in GIS and those in Smart Cities ICTs.

To conclude this paper, let us present Figure 29 showing the main links between pillars.

But the history of the links between urban planning and computing will continue to evolve in the coming decades. And presumably, novel key-concepts will emerge in order to plan more sustainable cities and in which people can have a better quality of life.

REFERENCES

[1] Al Nuaimi, E., Al Neyadi, H., Mohamed, N., & Al-Jaroodi, J. (2015). Applications of big data to smart cities. Journal of Internet Services and Applications, 6:25, doi: 10.1186/s131740015-0041-5.

[2] Batty, M. (2013). Big data, smart cities and city planning. Dialogues in Human Geography, 3(3), 274-279, doi: 10.1177/2043820613513390.Baxter R.S., Echenique M.H. & Owers J. (eds.) (1975) Urban Development Models, Lancaster, Construction Press. 343 pages. ISBN-13: 978-0-608-13089-7.

[3] Baxter R.S. (1976) Computer and Statistical Techniques for Planners, Methuen Press 1976, 336 pages.

[4] Blasi C., De Lotto I., Galimberti R., & Padovano G. (1968) A program for computer aided urban planning. CALCOLO, June 1968, Volume 5, Issue 2, pp. 229–249. Can be downloaded from https://link.springer.com/article/10.1007%2FBF02576109.

[5] Bouattou Z., Laurini R., Belbachir H. (2017) Animated Chorem-based Summaries of Geographic Data Streams from Sensors in Real Time. Journal of Visual Languages & Computing. April 2017, pp. 54-69.

[6] Cherni I., Ouertani S., Faiz S., Laurini R., Servigne S. (2013) Chorems: A new tool for Territorial Intelligence. 29th Urban Data Management Symposium, UDMS 2013, London, UK, May 29-31, 2013, Urban and Regional Data Management 2013, edited by C. Ellul, S. Zlatanova, M. Rumor and R. Laurini, Fancis and Taylor, London, pp. 67-76.

[7] Chrisman C. (2004) Charting the Unknown, how computers mapping at Harvard became GIS. Copyright ESRI. Can be downloaded from https://users.cs.duke.edu/~brd/Historical/hlcg/HarvardBLAD_screen.pdf

[8] Couclelis H (1992) People Manipulate Objects (but Cultivate Fields): Beyond the Raster-Vector Debate in GIS. Proceedings of the conference: Theories and Meth-ods of Spatio-Temporal Reasoning in Geographic Space, International Confer-ence GIS - From Space to Territory: Theories and Methods of Spatio-Temporal Reasoning, Pisa, Italy, September 21-23, 1992; pp. 65-77.

[9] De Chiara D., Def Fatto V., Laurini R., Sebillo M., & Vitiello G. (2011) A chorem-based approach for visually analyzing spatial data, Journal of Visual Languages and Computing,Volume 22 Issue 3, June, 2011, pp. 173-193.

[10] Egenhofer M. (1994) Deriving the Combination of Binary Topological Relations, Journal of Visual Languages and Computing (JVLC), vol. 5, no 2, June 1994, pp. 133-149.

[11] Foresman T.W. (ed) (1998) The History of Geographic Information Systems: Perspectives from the Pioneers. Prentice Hall PTR, 1998 - 397 pages.

[12] Gastaud E. (2017) From Internet Of Things To Smart Data For Smart Urban Monitoring. 2nd International Conference on Smart Data and Smart Cities, 4–6 October 2017, Puebla, Mexico. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLII-4/W3, 20, pp. 19-28.

[13] Goodchild, M.F. (2007). Citizens as Sensors: The World of Volunteered Geography. GeoJournal, 69 (4) pp. 211-221.

[14] Gopalakrishnan K. (2018) Deep Learning in Data-Driven Pavement Image Analysis and Automated Distress Detection: A Review. Submitted to the Open Journal Data.

[15] Hoel E., Cooke D., & Moreland B. (2013) History of GIS, The Foundations: 1940 to 1975. Can be downloaded from https://slideplayer.com/slide/4721226/

[16] Keita A., Laurini R., Roussey C., Zimmerman M (2004) Towards an ontology for urban planning: The towntology project. Proceedings of the 24th Urban Data Management Symposium, UDMS'2004, Oct 2004, Chioggia, Italy. pp.12.1-12.14, 2004.

[17] Kothuri R.K.V., Ravada S., & Abugov D. (2002) Quadtree and R-tree Indexes in Oracle Spatial: A Comparison using GIS Data. Proceedings of the 2002 ACM SIGMOD international conference on Management of data, pp. 546-557.

[18] Laurini R. (1985) Graphical data bases built on Peano space-filling curves. The Eurographics Association, 6th International Conference, Nice, North-Holland, pp. 327-338.

[19] Laurini R. & Thompson D. (1993) Fundamentals of Spatial Information Systems. Academic Press, (A.P.I.C. Series, No 37), March 1993.

[20] Laurini R. (1998) Spatial Multidabase Topological Continuity and Indexing: a Step towards Seamless GIS Data Interoperability. International Journal of Geographical Information Sciences, vol. 12, 4, June 1998, pp. 373-402.

[21] Laurini R. (2001) Information Systems for Urban Planning: A Hypermedia Cooperative Approach, Taylor and Francis, 308 p. February 2001.

[22] Laurini R. (2017) Geographic Knowledge Infrastructure: Applications for Territorial Intelligence and Smart Cities. Elsevier and ISTE, 312 pages.

[23] Laurini R, & Favetta F (2017) About External Geographic Information and Knowledge in Smart Cities. 2nd International Conference on Smart Data and Smart Cities, 4–6 October 2017, Puebla, Mexico. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLII-4/W3, 201

[24] Laurini R., Servigne S. & Favetta F. (2016) An Introduction to Geographic Rule Semantics. In Proceedings of the 22nd International Conference on Distributed Multimedia Systems (DMS 2016), Salerno, Italy, November 25-26, 2016. Published by Knowledge Systems Institute, ISBN: 1-891706-40-3, pp. 91-97.

[25] Mathew J. (2013) City as a Customer. Can be downloaded from http://www.frost.com/c/10046/blog/blog-display.do?id=2377335.

[26] McEachren A.M. & Kraak M.J. (1997) "Exploratory Cartographic Visualization: Advancing the Agenda". Computers & Geosciences, 23(4), pp. 335-343.

[27] Moosavi V. (2017) Urban morphology meets deep learning: Exploring urban forms in one million cities, town and villages across the planet. Sumitted to Environment and Planning B. Can be downloaded from https://arxiv.org/abs/1709.02939

[28] Morgan T. (2008) Business Rules and Information Systems: Aligning IT with Business Goals. Addison-Wesley. 384 pages.

[29] Randell, D. A., Cui, Z. & Cohn, A. G. (1992). A Spatial Logic Based on Regions and Connection, Proc. 3rd Int. Conf. on Knowledge Representation and Reasoning, Morgan Kaufmann, San Mateo, pp. 165-176.

[30] Ross R. G. (2011) More on the If-Then Format for Expressing Business Rules: Questions and Answers, Business Rules Journal, vol. 12, No. 4 (Apr. 2011), URL: http://www.BRCommun 2002ity.com/a2011/b588.html.

[31] Samet H. (1989) The design and analysis of spatial data structures. Addison-Wesley Publishing Co., 1989.

[32] Shekhar S. & Zhang P. (2006) Spatial Data Mining: Accomplishments and Research Needs. Can be downloaded from: http://www.spatial.cs.umn.edu/paper_ps/giscience.pdf

[33] Shneiderman B. (1997) Designing the User Interface. Third edition. Addison-Wesley Publishing Company. 600 pages.

[34] Shokoohi-Yekta M. (2018) Deep Learning for Smart Cities. Can be downloaded from https://www.gitex.com/__media/Mohd-Shokooji-Yekta-_-Apple.pdf.

[35] Teller J. (2007) Ontologies for an Improved Communication in Urban Development Projects. In Ontologies for Urban Development, edited by J. Teller, Springer, 2007, pp. 1-14.

[36] Wang L., & Sng D. (2015) Deep Learning Algorithms with Applications to Video Analytics for A Smart City: A Survey. Computer Vision and Pattern Recognition. Can be downloaded from https://arxiv.org/pdf/1512.03131.pdf