What (Smart) Data Visualizations Can Offer to Smart City Science (*)

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Abstract: Understanding the complexity and dynamicity of cities, as well as predicting and leading their evolutions, are topics of interest of new scientific disciplines such as smart city and city science. The development of better urban theories and simulation models could be fostered by both the availability of suitable datasets illustrating several urban perspectives and approaches being able to actively explore them in order to reveal patterns, relationships and meaningful data facets hidden there. In this context, data visualization – namely information visualization and visual analytics – is more than a promising research field to get new insights into data evidence. Its holistic approach couples pictorial representations, human factors and data analysis in order to enforce viewers' cognitive process of learning. In this paper we aim at providing an overview of the data visualization problems by reviewing current efforts into urban visualization, especially when considering two critical city issues: urban planning and energy efficiency. In particular, our objective is two-fold: presenting the most common approaches to data visualization disciplines and contextualizing them into the most advanced European initiatives and projects. In parallel, we introduce some hints about the most promising research areas and challenges that the domain experts could tackle in the very next future.

Key words: smart cities, data visualization, visual analysis, urban planning, energy efficiency.

Cities are complex systems where the global picture of the urban dynamics is given by the sum of several, evolving and intermingled networks. As a whole, they present non-static features as well as strong and varied interactions among all the main actors involved. Indeed, the many components characterizing an urban eco-system involve natural, morphological, socio-demographic, economic, cultural, and political facets

(*) The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 611307 (INSIGHT Project).

among others. Moreover, as living entities, the way people create social interactions, give functionalities to the architecture, benefit from services and infrastructures, or connect different areas of the urban fabric introduces a further level of complex dynamics being often difficult to grasp. It turns out that this limit of knowledge negatively affects the comprehension of what a city is, as well as how it could evolve. In turn, this problem seriously affects the setting-up of urban development policies because it makes it difficult to foresee their impacts, strengths and unintended consequences.

Since we live in cities, we need to plan their space, growth and organization. But designing the future of them means more than providing buildings. Conceiving supporting structures and guaranteeing their efficient management are crucial points as well. In this context, and due to the complexity of the problem, managing to foster current and future organizations of cities should be carried out by innovative and interdisciplinary approaches, comprising networks / graph theory, complex system science and agent-based computational modeling. Such approaches are intended to describe, explain, and forecast the behavior of and interactions between different elements of the urban system according to a more mathematical point of view. This catches the abstract part of the problem very well, but to make model results more accessible to policy makers and urban planners, those strategies should be pushed a step further. In this sense, visual representations can provide concrete feedbacks on what policies are dealing with and catch hidden unconventionalities. In parallel, this approximation is expected to lower the barriers for the operational use of advanced urban simulation tools and enhance communication skills among stakeholders, domain experts and citizens.

■ Cities challenges

As stated in (Commission of the European Communities, 2011), the universe 'city' currently embodies a two-fold challenge: how to improve competitiveness while achieving social cohesion and environmental sustainability. Indeed, cities are fertile ground for science and technology, innovation and cultural activity, but at the same time, they are also places where problems such as environmental pollution, unemployment, segregation and poverty are concentrated.

The study of cities as 'systems' got its formal definition several decades ago, where those approaches considered cities as distinct collections of interacting entities, usually thought to be in equilibrium, and where the control on them could follow a centralized, top-down approach (McLOUGHLIN, 1969). During the last 20 years, however, there has been a shift in the way of thinking at them: complexity theory has raised the notion that (human) systems are never in equilibrium (HEPPENSTALL *et al*., 2012) so that the current image of a city is that of a 'living, self-organizing system' that evolves organically from the bottom up (BATTY, 2012). As our conception of urban systems is changing, urban planning concept transforms accordingly: nowadays, we consider cities under a decentralized, bottom-up perspective, in which the role of policy makers and urban planners is that of nurturing positive emergent phenomena and minimizing negative emergent properties, at least along six main dimensions - namely economy, mobility, environment, people, living, and governance (GIFFINGER *et al*., 2007).

The ideas of 'smart city' and city science (LAUBE *et al*., 1998; SOLECKI *et al*., 2013) emerged during the last decade as a fusion of ideas about how ICT might improve the overall functioning of cities. The ultimate goal of these urban sciences is to enhance performances, efficiency, and competitiveness by providing new ways of creating sustainable development and higher levels of quality of life (BATTY *et al*., 2012). Initially shaped as a very techno-centric concept, urban sciences are currently skipping the idea of ICT-driven cities to embrace a wider idea in which the use, coordination and integration of modern technologies (including transport or energy technologies, in addition to ICT) blend investment in human, social, and environmental capital too (CARAGLIU *et al*., 2009). In this context, data visualization not only might support the provision of scientific evidence for public action, but should facilitate stakeholders' engagement, communicate scientific evidences, and drive societal debates. In the following, we discuss such features in the framework of urban policy design and energy efficiency policies.

Urban planning

With the emergence of the open data movement, public administrations are beginning to give access to several amounts of data in many different formats (urban data systems). In parallel, the increasing penetration of modern ICT, such as smart phones, e-transactions, Internet social networks or smart card technologies, allows the automatic collection of a vast amount of spatial and temporal data, which combined with more traditional, cross sectional demographic and economic activity databases (e.g. census data), can be used to extract relevant information about urban dynamics. The development of new methods and tools for the acquisition, integration, management, analysis and visualization of data originated from multiple distributed sources is an urgent need. Huge opportunities are rising up from the explosion of available data, truly information mines. Handling and exploiting such resources might steer the whole urban planning process towards a more informed, heavily evidence-based approach. Consequently, the development of better urban theories and simulation models could be, not only possible, but desirable and advantageous. A comprehensive theoretical framework to address the many different questions related to urban development could gain valuable insight by coupling together recent advances in areas such as network theory or agent-based computational modeling, and the holistic and eclectic approach advocated by complexity science.

Certainly, cities will only be truly smart if these advances in terms of data and models are properly integrated into governance processes. While simulation models have been widely applied in areas like transportation planning and traffic engineering, there are fields – e.g. land use planning – in which the potential of urban models is still largely unexploited. Moreover, in many cases, the potential users do not have the skills to use such models or are not convinced of the benefits. To bridge this gap, the development of the models needs to be user-driven and based on a continuous dialogue between scientists and policy makers. In this context, a crucial role is played by new forms of information visualization and visual analytics, which can make model results more accessible to policy makers and urban planners. At the same time, such advances open the door to the development of new ways of citizens' engagement in the design and planning of their cities. For instance, it could be possible to capture the inputs from the community (e.g. by reconstructing citizens' opinion from data resources distributed throughout the Internet) as well as support an increased participation of citizens (e.g. through applications that allow citizens to monitor and report the system status in real time). User-specific interfaces and tools for the visualization of policy impacts in an intuitive and graphical manner can facilitate collaborative, multi-stakeholder policy assessment and decision making processes in which societal actors collaborate with experts in the generation and analysis of urban policies.

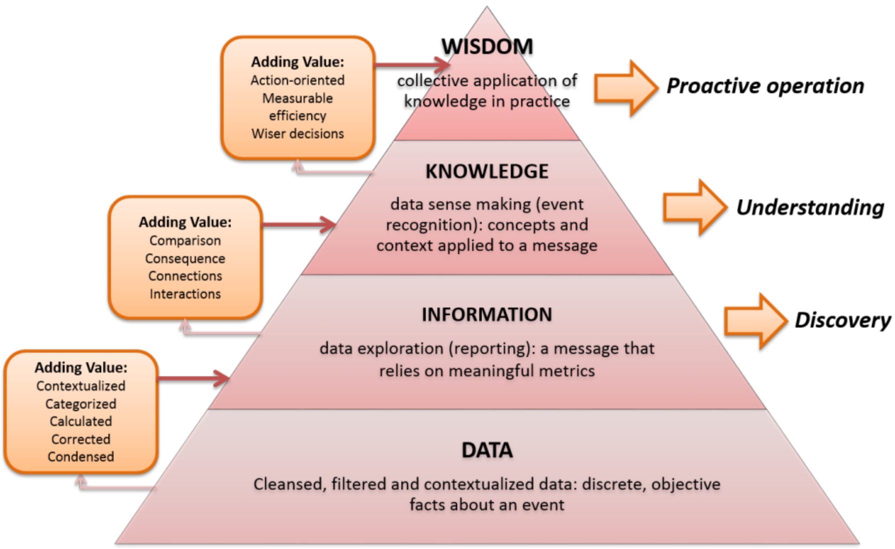
Energy efficiency

Energy efficiency is playing a growing role in local, national and European policy development, stated, for instance, through ambitious targets (European Commission, 2010; European Commission, 2011), which will require a profound transformation of energy production, transportation and consumption from now till 2050. Efficiency is widely recognized as the most cost-effective and readily available mean to address numerous energy-related issues, including energy security, the social and economic impacts of high energy prices, and concerns about climate change. To formulate long-term strategies and define cost-effective policies, policy makers need to better understand both the macro and micro-economic impacts of energy efficiency policies: this means evaluating their evolution according to factors such as the influence of consumer behavior, the influence of institutional factors, and the implications of trends in society and technologies. Cities and communities can achieve energy efficiency and sustainability objectives if suitable strategies are implemented. To reduce inefficiencies due to energy wastes, it is important to address efficient policies taking into account both the spatial composition and transformation in cities and regions (IMMENDOERFER *et al*., 2014). For instance, centralized electricity generation causes electricity production in large power stations far from the cities, thus affecting its distribution; houses and facilities are heavily energy consuming poles whether they have not built according to green protocols and efficiency criteria; urban land use is directly responsible in determining travel patterns and therefore the rate of fossil fuel vehicles use. Simultaneously, urban and regional energy efficiency strategies involve a series of prominent trade-offs: low density buildings provide more scope for distributed power and reduce heat island effects, but can increase transportation demands and night time heating demands; new developments provide more opportunities to incorporate energy efficiency measures and distributed power generation, but energy consumption in construction is substantial; telework or on-line shopping can reduce transportation demand, but can increase residential energy consumption or generate other types of trips. These and other examples show the importance of developing a multidimensional framework describing a holistic view of buildings and transport energy utilization incorporating sensitivity to the urban form and people's lifestyles. As in the case of urban planning, data availability and visualization tools are key factors to break up the most critical issues of the problem and assess policies effectiveness.

■ The 2D and 3D realm of visual data

Data visualization is a generic definition identifying a discipline whose aim is to communicate information to an audience through graphics and visual metaphors. The capability visualization has to convey a message is by exploiting the perceptual mechanisms of the human sight: this way, it enforces the whole cognitive process of learning, as well as providing powerful tools in dynamically revealing patterns, relationships, clusters, unknown facts and outliers (SHNEIDERMAN, 1996). Its ultimate goal is to transmit content in order to allow viewers to gain knowledge, get information and ease the understanding of the represented topic. The central point is that raw data are not worthy per se, but for the information / knowledge / wisdom analysts can extract (and thus represent) from there (see Figure 1). In other words, visualization acts like a bridge connecting data and their final users to help make sense of an, often messy, realm. In order to be effective, the choice of undertaking the most suitable visualization approach must take into account several factors such as: the goal it would be built for, the data at disposal, the analysis context, and the audience to target. Depending on the way these features combine, different possibilities arise.

Figure 1 - The pyramid of knowledge, from data to wisdom

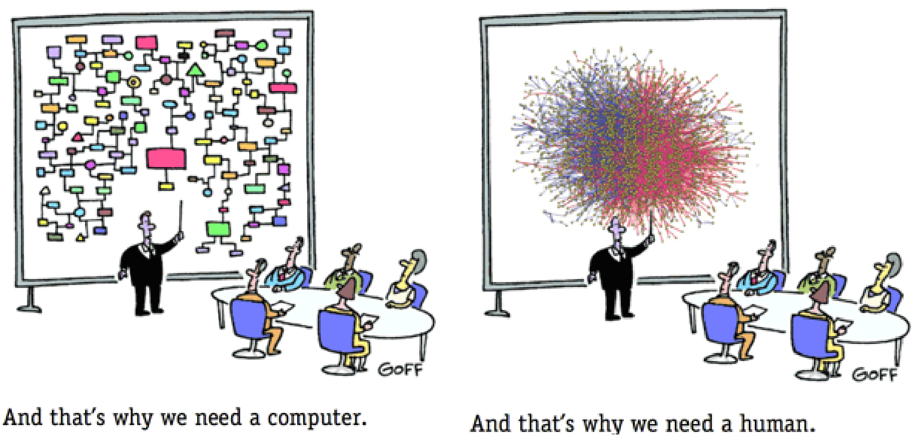


On the left, operational activities to perform to reach the next stage. On the right, the output of each stage. Data visualization techniques provide suitable means to climb up the pyramid.

Infographics, information visualization (IV), and visual analytics (VA)

One of the most challenging issues related to (big) data concerns the analysis of overwhelming amounts of multi-dimensional, multi-source, time-varying, disparate, conflicting, and dynamic information sources. Being able to properly handle them requires tangible forms of raw data representations, so that human capabilities of evaluation, reasoning and judgment could be exploited (see Figure 2). Infographics, IV and VA approaches go towards the same direction but through different paths. For instance, infographics favor a static, visual representation of data and are usually intended for dissemination purposes: for these reasons, they are more descriptive and do not allow users to have a direct interaction with them. On the other hand, IV deals with conveying abstract information in intuitive ways in order to "see, explore, and understand large amounts of information at once" (THOMAS & COOK, 2005).

Figure 2 - A funny, yet really fitting, representation of the need of both ITC tools and visual skills for reasoning (Images © by Ted Goff)



Finally, VA "combines automated analysis techniques with interactive visualizations for an effective understanding, reasoning and decision making on the basis of very large and complex datasets" (KOHLHAMMER *et al.*, 2011). As clearly stated from the definitions above, both IV and VA stress the interaction among users and the visualization interface. But in the former case, the interaction is more focused on enabling viewers to gain knowledge about the internal structure of the data and causal relationships in them; in the latter case, the exploratory interaction is directed towards analytical and reasoning tasks. Active exploration of (visual metaphors of) data helps viewers to detect salient aspects of data in the sense of perceiving the salient features of data, including commonalities and anomalies. However, to design the proper visualization scheme many hurdles could affect the achievement of a perfect perceptual thinking: among others, data incompleteness, inconsistency, and deceptiveness; datasets stunning scale; the rapidity in collecting them being several order of magnitude bigger than our ability to analyze it; the capability to detect only the relevant information against the massive amounts of available information.

In the context of urban science, IV and VA disciplines can provide a strong support to efficiently solve the issues introduced in the previous sections. Several examples of successful applications to concrete case studies have appeared in recent years to reveal cities facts and dynamics under different points of view. For instance, different kinds of mobility (e.g. transport systems usage) have been studied according to a number of digital traces left by people across the urban fabric, such as cell phones, social networks activities and photos (GIRARDIN *et al*., 2008; READES *et al*., 2009; JANKOWSKI *et al*., 2010). Depicting people movements due to economic reasons has also recently shown its potential impacts in understanding urban dynamics (PIOVANO *et al*., 2014). A list of all the most interesting works would be undoubtedly incomplete and not exhaustive. However, to have a clearer picture of the interest around those disciplines, we suggest the interested readers look at the number of dedicated websites and forums aiming at discussing and presenting visualization examples, software resources and tutorials [1]. On the other hand, recent surveys about the state-of-the-art in IV and VA tools show the dynamicity of this research topic, in both the academic and open source world (HARGER & CROSSNO, 2012) and in professional markets (ZHANG *et al*., 2012).

Geographic representations

Nowadays, the number of sensors being able to capture geographical coordinates of both people and things is growing and spanning a number of case studies. Therefore, the quantity of geo-referenced information is increasing accordingly, as well as their natural representations, that is maps. In particular, city maps are the standard expressions to convey a sense of geographical order into the urban landscape. As they are the visual

[1] e.g. www.visualizing.org, www.floatingsheep.org, http://blog.visual.ly/, http://flowingcity.com/, www.visualcomplexity.com, http://fellinlovewithdata.com, http://urbanmovements.co.uk/, and http://oobrien.com/

representation of the spatial relationships among the different urban structures, they intrinsically reflect the static features contained in them. Thinking of cities as living entities entails considering a wide variety of interactions among their main actors: this way, their dynamic properties and the varying perspectives of dwellers are determined. The whole urban net is made up of a complex systems of knots which reflect how people actually perceive city spaces. Thus, successful approaches to the urban problem should consider alternative representations of the city dynamics in order to achieve a complementary but powerful insight upon the actual urban space usage. A first way to impulse such objective could be to exploit the mapping paradigm to represent city facts on the top of classic topographical representations. However, a real raise in the visual understanding would occur by coupling IV- and VA-oriented approaches as shown in Figure 4. In both cases, maps cease to be simple maps and become services displaying other information and create knowledge (ROSEN, 2012).

In the very last years, at least three factors have actively contributed to realize such a shift in conceiving cartography. In particular, the popularization of GIS services; the increasing amount of tools and companies furnishing services of map customization and diffusion; and the creation of agile standards to manage geographical representations independently from the platform and the domain of use. More in detail, a geographic information system (GIS) integrates hardware, software, and data for capturing, managing, analyzing, and displaying all forms of geographically referenced information. By way of example, just consider mobile technologies: thanks to all sorts of sensors embedded in smart-phones and tablets, people are turning into living antennas capturing and (sometimes) sharing their digital traces such as social network activities, time spent in traffic jams, phone calls, e-shopping, health checks, sport performances and so on. In this context, GIS tools provide a new way to look inside those data, at both coarse – for instance, by aggregating data at citizens, ethnic groups, or customer profiles grain – and finer levels, that is by considering singular person traces. Therefore, it is not unexpected at all that commercial tools such ArcGIS suite and their open counterparts like QGIS have been increasingly adopted to map things / people where they are and move to, show densities, analyze temporal evolutions, and explore urban environments according to a data-centric paradigm. Simultaneously to this new wave of depicting data content, researches focused their attention on the canvas too – that is maps. Google Maps is maybe the most well-known example in this context: born as a web mapping service to provide traditional, cartographic information – either by satellite imagery or street map designs – it moved little by little towards service-oriented offers, for instance in terms of route-planning and traffic information. The use of APIs (application programming interfaces) allows registered users to develop their own applications by exploiting Google tiles and geographical services. In that moment, geography started to be the perfect excuse to tell a history with data. In the wake of Google's success, other private providers such as Apple, Microsoft, Nokia, and Yahoo started to offer their own map tiles and geo-web services. In order to overcome traditional restrictions on use or availability of such map information, collaborative projects started to arise aiming at encouraging the development and distribution of free geo-spatial data for everybody. This is the case, for instance, of Openstreetmap whose foundation motivated the creation of a free editable map of the whole world. Differently from worldwide companies approach, Openstreetmap is organized around the contributions of thousands of volunteers across the world. To keep consistency over all the peers' inputs and communicate across different environments or platforms, a topological data structure has been defined to store, organize and share all the information in a structured way. With a similar goal in mind, another couple of open standard formats, namely GeoJSON and its extension TopoJSON, have been introduced to encode collections of simple geographical features along with their non-spatial attributes using JavaScript Object Notation. Those standards have been recently popularized because of their suitability to represent geographical features in web-based environments based on the most recent, related technologies such as HTML5 and CSS3.

3D city models

The fields introduced above mostly work on a 2D basis. However it could be possible to build efficient visualization techniques by using the depth information too, as in the case of 3D city models. They are a (virtual) digital representation of the earth's surface and its related objects such as buildings, vegetation, and some man-made features belonging to an urban area. With respect to other bi-dimensional techniques, a crucial feature in these models is the complete exploitation of all the spatial directions. 3D models have a long history and were introduced for a very wide range of purposes. Practical contributions showing how to apply those models to real domains comprise and are not limited to: supported analysis and design of urban areas; CCTV monitoring systems; spatial decision support; crisis management; 3D noise modeling; architectural documentation; mobile 3D city maps; urban land management; buildings thermal analysis. The common denominator in all the proposed examples concerns the use of a unique geometric model being equal to the city to be modeled, and according to the principle that the 3D representation should be kept separated from those 'external' features characterizing the operational domain. This way, the urban model can be created once and for all while the associated domain could change and adapt according to the analyst's needs. Basically, semantically enriched, virtual 3D city models keep in their re-usability and flexibility features the very reasons of their success. But, in order to be really effective and fully exploit virtual 3D city models, a common data model for storage and exchange of geometry, semantics and relations of the modeled features are required. To satisfy these requirements, several proposals have been made in the corresponding literature but currently the City Geography Markup Language [2] is the most successful of them [3].

It has been the first approach aiming at standardizing the way to model and exchange 3D city and landscape to be quickly adopted at an international level. CityGML is defined as an information model for describing 3D objects with respect to their geometry, topology, semantics and appearance. Descriptors handling generalization hierarchies between thematic classes, aggregations, relations between objects, and spatial properties are also presented in its specifications. Its high scalability is one of its best prerogatives: it allows to model not only the whole urban fabric and its single components but also whole sites, districts, cities, regions, and even countries. Another key factor in its success is being an open standard, and as such, being able to be used free of charge and extended by third parties. Other features of CityGML definition include: geospatial information model (ontology) for urban landscapes based on the ISO 191xx family; GML3 representation of 3D geometries, based on the ISO 19107 standard; representation of characteristics of object surfaces (e.g. textures, materials), including transportation facilities (both graph structures and 3D surface data) and land use (representation of areas of the Earth surface dedicated to a specific land use; five different Levels of Detail (from LOD0 to LOD4, each of them including both geometrical and semantic details: see Table 3 and Figure 5 for more details) allowing simultaneous, multiple, coarse-to-fine representations; and, Application Domain Extensions (ADE) which allows to

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[2] CityGML: http://www.citygml.org/

[3] There are currently several other standards and providers of 3D city models. Readers interested in a closer examination of this topic could refer, for instance, to the websites of some of the most important companies involved in this business segment, such as BLOM, ESRI and NAVTEQ.

extend CityGML functionalities, in terms of additional attributes and relations, by adding personalized, domain-specific descriptors. The creation of new ADEs is typically performed through the UML (Unified Modeling Language™), a language that specifies how to construct, visualize, and document the artefacts – that is some information used or produced by a software development process – of an object-oriented (OO) software system. Another common way to extend CityGML structures consists in introducing generic classes and attributes: the strong point here is the ease and flexibility of extension, but at the cost of hampering interoperability, since there is no common schema for extensions.

Table 1 - A list of relevant FP7 EU projects explicitly tackling data visualization topics for urban policy design

Project name	*Dates*	*Description*
+Spaces	01/01/2010 – 30/09/2012	Combining social media and virtual worlds to model real world behavior
Crossover	01/01/2011 – 30/06/2013	Developing an international roadmap and detailed case studies on specific applications of ICT solutions for policy modeling by creating/reinforcing clusters of experts across different global communities
Crossroad	01/01/2010 – 31/12/2010	Definition of a roadmap for ICT research in the field of governance and policy modeling
e-Policy	01/10/2011 – 30/09/2014	Analyzing the results of social simulations, with the aim of informing regional planning processes
EveryAware	01/03/2011 – 28/02/2014	Combining sensing technologies, networking applications and data-processing tools to enable participatory sensing; developing shared perception of environmental issues; driving behavioral changes
Fupol	01/10/2011 – 30/09/2015	Integrating advanced visualization tools across the entire policy life-cycle
Impact	01/01/2010 – 31/12/2012	Developing computational models to facilitate policy deliberations at a conceptual, language-independent level
Nomad	01/01/2012 – 31/12/2014	Developing systems being able to automatically collect, analyze and interpret opinions expressed through the Web
Ocopomo	01/01/2010 – 30/04/2013	Combining e-participation and agent-based social simulation to develop narrative scenarios and transform them into formal policy models
Propolis (*)	01/01/2000 – 30/06/2003	Integrating simulation models and GIS techniques with interactive visual analytics tools in order to allow policy makers to assess land use and transport policies
UrbanAPI	01/09/2011 – 31/08/2014	Increasing stakeholder engagement in urban planning through the development of virtual reality visualizations of neighborhood development proposals

(*) Project under 5th RTD Framework Programme

■ Current worldwide efforts and proposals

Urban planning

Throughout the last decade, several European projects have begun to explicitly deal with data visualization approaches to be integrated within decision support tools for urban and regional policy assessment and collaborative planning (see Table 1). PROPOLIS [4] was one of the pioneering projects as they integrated strategic LUTI models and GIS techniques with interactive visual analytics tools, conceived mainly to be used by policy makers for the integrated assessment of land use and transport policies. Several projects recently launched are developing visual interfaces for participatory urban planning: e-POLICY [5] uses visual analytics components to analyze the results of social simulations, with the aim to inform regional planning processes and present the final conclusions in a form that is understandable for the different stakeholders, through charts, graphs and animated maps; FUPOL[6] adopts a wider vision aimed at integrating advanced visualization tools across the entire policy life-cycle and adapting information visualization to different levels of users' expertise; and UrbanAPI [7] focuses on interactive visualizations of possible urban planning interventions at different scales, from 3D virtual and augmented reality applications for urban design at neighborhood scale, to land use simulation at urban and regional scale represented as an overlapping layer on a geographical map or through graphs and charts summarizing the main results. Lastly, the main topic the INSIGHT [8] project is focused on is to understand how data-related ICT can help European cities formulate and evaluate policies to stimulate a balanced economic recovery and a sustainable urban development after the last economic crisis. The core idea is to take advantage of multiple distributed sources available in the context of the open data, the big data and the smart city movements (paying attention in particular to the retail, housing, and public services sectors) to understand urban development patterns. To that end, it is important to enhance current spatial interaction and location models for the sectors of

[4] http://www.ltcon.fi/propolis/
[5] http://www.epolicy-project.eu/
[6] http://www.fupol.eu/
[7] http://urbanapi.eu/
[8] http://www.insight-fp7.eu/

interest with data evidence in order to detect the main drivers of their distribution across cities. Their integration into the urban simulation tools currently available, as well as the development of innovative visualization tools, will help stakeholders to foster decision-making policies by facilitating the analysis and interpretation of the simulation outcomes.

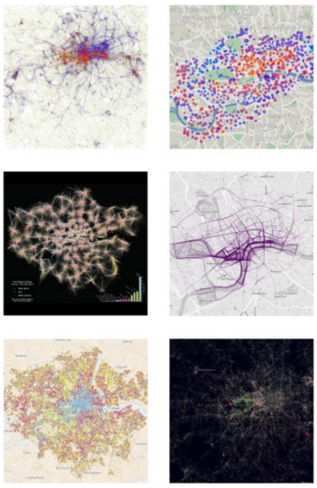
Table 2 - A list of relevant FP7 EU projects explicitly tackling data visualization topic for energy efficiency

Project name	*Dates*	*Description*
Besos	01/11/2010 - 31/10/2013	Developing an advanced energy management system to monitor and manage energy efficiency in smart cities facilities such as public lighting and urban heating systems, public buildings, electric vehicles, and residential consumers
CitInEs	01/10/2011 - 31/03/2014	Providing analytical tools which defines a complete and coherent energy model of cities by offering a dynamic representation of the territories for the analysis of energy systems, energetic opportunities, and long-term environmental and economic impacts of territorial projects
Dimmer	01/10/2013 - 30/09/2016	Creating a system integrating an extended version of BIM (Building Information Models) models at district level (DIM), advanced 3D virtual, urban representation and real-time data from sensors and user feedbacks
Hesmos	01/09/2010 - 31/12/2013	Developing software and methods for energy simulation and management of energy efficiency during maintenance by extending eeBIM models to n- dimensions (3D + time + costs + …)
i-Scope	15/01/2012 - 15/01/2015	Developing an open platform providing smart web services by exploiting, on the one hand 3D urban models and on the other, integrated information about geometric, semantic morphological and structural descriptions of the cities themselves
iUrban	01/10/2013 - 30/09/2016	Implementing an intelligent tool capable of capturing real-time data (energy consumption and production) from Distributed Energy Resources installed around the cities.
NRG4CAST	01/12/2012 - 30/11/2015	Developing a framework being able to control, manage, analyse and predict behaviour in electric power networks, gas or hot water distribution systems by monitoring energy behaviour in different network layers: single buildings, neighbourhoods and urban environments
Semanco	01/09/2011 - 30/11/2014	Building an open platform where energy consumption related data – often dispersed and owned by many different organizations - are presented and visualized through a set of suitable visualization metaphors and 3D models.

Apart from projects, there are also several international initiatives focusing on the collection and visualization of real-time information on urban dynamics. Two relevant examples are LIVE Singapore! and Ville Vivante.

LIVE Singapore![9] aims at creating a set of applications for the collection and distribution of a large number of streams of very different kinds of data, such as cell-phone calls and text messages, weather information, or traffic data. Ville Vivante[10] is a visualization project whose main objective is to represent people movements within the city of Geneva through the digital traces created by mobile phones. Other recent works are developing strategies to depict stakeholders' knowledge concerning very specific sites (FAGERHOLM *et al*., 2012; EISNER *et al*., 2012); analyzing and evaluating the strengths and weaknesses of current GIS tools for participatory governance (McCALL, 2003; VOSS *et al*., 2004), (McCALL & DUNNE, 2012); or investigating how to use Participatory GIS to build a shared vision of local knowledge between different local stakeholders (REYES-GARCIA *et al*., 2012). Figure 3 shows some examples of data visualizations related to the city of London.

Figure 3 - Some examples of London cartography



From left to right, top to bottom: tourists' *vs*. locals' Flickr geo-tagged photos (1); real-time mapping of bike sharing lots activities (2); a year of fire engine callouts (3); where people run (4); crime map of London (5); tweets languages (6)

(1) https://www.flickr.com/photos/walkingsf/sets/72157624209158632/
(2) http://bikes.oobrien.com/london/
(3) http://spatial.ly/2013/06/mapped-londons-fire-engine-callouts/
(4) http://flowingdata.com/2014/02/05/where-people-run/
(5) http://www.ft.com/intl/cms/s/2/80a228dc-f3fa-11e2-942f-00144feabdc0.html#axzz2aF1StOY
(6) http://urbanmovements.co.uk/2012/10/23/detecting-languages-in-londons-twittersphere/

9 http://senseable.mit.edu/livesingapore/index.html

10 http://www.villevivante.ch/

Energy efficiency

Energy data analysis – especially in the context of household and economic activities energy usage, optimization of energy systems and urban energy distribution – is particularly suitable for applying visual approaches to get deeper insights. Energy data is a typical example of big data because it often consists of billions of information units, sometimes updated in nearly real-time and presented / produced in several, heterogeneous forms. As these data are combined with other data sources (e.g. socio-demographic indicators or weather forecasts), the overall complexity would increase accordingly, as well as the need to communicate results in a clear and smart way. Traditional approaches to visually depict energy data encompass both geographic and diagrammatic representations. In particular, map-based representations are particularly suitable to put abstract data into their geographical context. Several examples of such visualizations can be found. (REUL, 2012) suggests the adoption of a community-level energy mapping tool aiming at providing broadly accessible information about energy services, improving the level of coordination among service providers and promoting efficient measures and responsible behaviors amongst energy consumers. Urbmet [11] provides an interactive web-based visualization environment aiming at exploring and analyzing energy resource consumption in US cities; the New York city web-map [12] is estimating the total annual building energy consumption at both block and tax lot level; and the interactive energy map of Los Angeles [13], displaying average monthly energy consumption at the census block group level between January 2011 and June 2012. Mapdwell for Cambridge MA and Washington DC [14], the Solar Atlas of Berlin [15] and the Solar Cadastre of Paris [16] focus on the potential benefits of installing photovoltaic panels on the top of building roofs.

Concerning visual analytics, several European initiatives and projects promote the integration of visual analysis techniques into decision support tools related to the energy domain (see Table 2). Semanco [17] aims at

11 http://urbmet.org/

12 http://modi.mech.columbia.edu/resources/nycenergy/

13 http://sustainablecommunities.environment.ucla.edu/maproom/index.html

14 http://en.mapdwell.com/cambridge

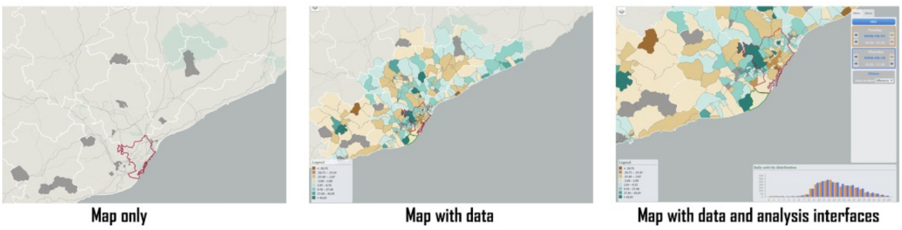
15 http://www.businesslocationcenter.de/wab/maps/solaratlas/

16 http://www.cadastresolaire.paris.fr/

17 http://www.semanco-project.eu/

building an open platform where energy consumption data are presented and visualized using graphs, 3D models and general diagrams; SimStadt [18] relies on virtual 3D city models to assist urban planners and city managers in the design and implementation of low-carbon energy policies; i-Scope [19] focuses on the optimization of energy consumption through a precise assessment of solar energy potential and energy loss at building level; Dimmer [20] analyses the correlation between buildings use patterns and real-time feedback of energy-related behaviors with the support of a system integrating an extended version of BIM (Building Information Models) models at district level (DIM), advanced 3D virtual urban representation and real-time data from sensors and user feedbacks; and Crystal City, developed for the CitInEs project [21], proposes an analytical tool offering a dynamic representation of territories for the analysis of energy systems and long-term environmental and economic impacts of territorial projects.

Figure 4 – A practical example of how a visual analysis could be built on the basis of a traditional geographical representation



■ Conclusions and future opportunities

As previously seen, data visualization has been experiencing an exponential growth in terms of both scientific interest and successful applications on real case studies. At least two are the key aspects of its success: first, its capability to efficiently communicate information to viewers by presenting it through suitable visual representations of the underlying data; and second, simultaneously simplifying and magnifying particular analytical tasks such as making comparisons and determining causality. In

[18] http://www.simstadt.eu/
[19] http://www.iscopeproject.net/
[20] http://www.fit.fraunhofer.de/en/fb/ucc/projects/dimmer.html
[21] http://www.citines.com/

this context, city science disciplines, such as urban planning and energy efficiency, provide perfect challenging testing grounds, especially whenever policy makers and stakeholders need to take informed decisions based on concrete facts evidence. However, although several advances have been made in successfully coupling visualization techniques into the domain of urban decision making policies, there are still several issues to overcome. To that end, more research efforts from both the academic and commercial sides are needed to introduce innovative elements and push current limitations further and further. For these reasons, we complete our overview by briefly outlining some of the most remarkable and promising research areas, according to two distinct points of view.

(Big) data issues

Data availability, quality and integration

Beyond doubt, the last decade brought a wide-spreading dowry of datasets from different sources, but despite this abundance, data requirements – basically in terms of accessibility and quality – are not always met, hindering their operational use at a large scale. In this context, a first step could be an international effort towards the definition of standards being able to harmonize the processes of acquiring, gathering and publishing data (and the associated meta-data) to improve quality issues. Moreover, given the heterogeneous nature of those data sources, new database architectures are required to store and integrate them in a coherent, operationally efficient and cost-effective way.

Open access and privacy

Incentives to promote open access policies would lead to more virtuous practices in terms of fast access and sharing information worldwide. Open access paradigm might concern not only government and public agencies but private citizens too. Of course their use and releases have to come under trustful, transparent and private conditions[22].

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[22] See, for instance: http://www.weforum.org/issues/rethinking-personal-data

Need for speed

As big data production rate is growing faster and faster, the need to deal with just the relevant data, at different levels of detail and as fast as possible, becomes a complex challenge. Moreover, the (visual) analysis capability should keep the pace in terms of effectiveness and efficiency. To meet all these requirements, real-time interaction and latency reduction (MANSMANN *et al*., 2012) should be carefully addressed. In this sense, research could lean on improving hardware equipment (e.g. more powerful parallel processing) or develop more distributed computing approaches (e.g. grid-like).

Looking for data skills

Data analysis bottleneck does not always come across software or hardware limitations: a common complaint among insiders of the field is about the scarcity of specialized statisticians [23]. Thus, a great challenge will be promoting both academic and professional vocational training centers to compensate for actual personnel lack.

Visualization issues

More intuitive, user-specific interfaces

Current visualization tools are still largely designed for technical experts, limiting the opportunities for a wider user involvement. Thus, there is a need to develop more intuitive interfaces to address the requirements of different communities and achieve a better integration of quantitative and qualitative information.

Good practice and visualization language learning

A common saying states that a picture is worth a thousand words. Even if it describes the core of data visualization discipline, it is not completely true, especially when bad visualization practices are used. Thus, to properly exploit visualization capabilities, it is essential to have the best visualization experts working on data representations. On the other hand, general

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[23] See for instance: http://www.nytimes.com/2009/08/06/technology/06stats.html?_r=1 and http://archive.wired.com/culture/culturereviews/magazine/17-06/nep_googlenomics?currentPage=1 (last access 18/09/2014).

audiences might also be taught to correctly understand and interpret graphic languages.

Integration between visualization and (spatial-temporal) analytical functionalities

Geo-visualization is a fast growing area, but there is still little integration with data analysis functionalities. Recent research is tackling the problem of combining data mining tools with iterative visualization on top of specific geographical representations (AUVIL *et al*., 2007; MOZZAFARI & SEFFAH, 2008; von LANDESBERGER *et al*., 2012). Geo-referenced data are constantly increasing but until recently, their analysis has mainly taken a static perspective. As all spatial phenomena evolve over time, temporality is central to our understanding of spatial processes. However, this is still a largely unexplored territory, mainly due to technical difficulties in dealing and significantly representing or comparing 4 dimensions at a time.

Mobile vs. desktop applications

Desktop approaches to visual representations and analysis tools do not usually apply well when embedded into mobile apps, because they do not take advantage of mobile interaction features (typically, touches and gestures). The open challenge for researchers and practitioners is therefore to design more natural and intuitive interactions / gestures / metaphors to work for touchable data visualizations.

Tools for annotating

With respect to other components, annotation tools are somehow an underestimated feature in a visualization design. Indeed, by taking notes, users help themselves to fill the semantic / logic gap between what they see and their interpretation of visual cues in different contexts and with different objectives. Therefore, a research challenge would be to provide smart annotation tools in order to give to visualization practitioners a complete offer to enhance their visual thinking.

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Annex

Table 3 - Main features of different CityGML Levels of Details (LoD

	LOD 0	*LOD 1*	*LOD 2*	*LOD 3*	*LOD 4*
Model scale description	Regional landscape	City Region	City districts projects	Architectural models (outside), landmarks	Architectural models (interior)
Class of accuracy	Lowest	Low	Middle	High	Very high
Absolute 3D point accuracy (position / height)	Lower than LOD1	5/5 m	2/2 m	0.5/0.5 m	0.2/0.2 m
Generalization	Maximal generalization (classification of land-use)	Object blocks as generalized features; >6 * 6 m/3 m	Objects as generalized features; >4 * 4 m/2 m	Objects as real features; >2 * 2 m/1 m	Constructional elements and openings are represented
Building installations	-	-	-	Representative exterior effects	Real object form
Roof form/structure	-	Flat	Roof type and orientation	Real object form	Real object form
Roof overhanging parts	-	-	n.a.	n.a.	Yes
City furniture	-	Important objects	Prototypes	Real object form	Real object form
Solitary vegetation object	-	Important objects	Prototypes >6 m	Prototypes >2 m	Prototypes, real object form
Plant cover	-	>50 * 50 m	>5 * 5 m	<LOD2	<LOD2

Figure 5 - A representation of how the Levels of Details change across the 5 LOD classes defined in CityGML specification (see Table 1 for detailed descriptions of LODs)