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Cities in transformation. Computational urban planning through big data analytics

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Abstract. Future scenarios foresee a city as a fragmented and uneven system in relation to rapidly evolving environmental, economic and social phenomena. The traditional urban planning tools, based on a theoretical-predictive approach, adapt poorly. We need to rethink how to govern the transformations of a city, which can be described by models of urban metabolism. City Sensing has changed the way a city is explored and used. With the transition from digitisation to datafication, through a computational approach, one can process georeferenced datasets within algorithms in order to achieve a higher quality of the project. This process exploits data provided by public administrations, companies and citizens taking part in inclusive and adaptive urban planning.

Keywords: City Sensing; Datafication; Big Data Analytics; Computational Urban Planning; Adaptive and Inclusive Urban Planning.

The Contemporary World's Fast Urbanisation

Nowadays about 55% of the world's population lives in urban areas. This percentage is likely to reach 68% by 2050. Globally, by 2030 the number of megacities is expected to reach 43 (United Nations, 2018). In relation to what can be deduced from the data shown, cities represent one of the major problems of the contemporary era to face both, on the one hand, environmental issues (energy consumption, pollution) and, on the other hand, economic and social ones (Fig.1).

Davis (1965) already wrote that urbanised societies, in which most people lived, crowded together in cities, represented a new and fundamental step in man's social evolution. It was clear that modern urbanisation could be best understood in terms of its connection with economic growth and availability of resources. Moreover, in those days, there was hardly any widespread perception of the problems that urbanisation could imply and only a few non-profit international associations, such as the Club of Rome, founded in 1968, started to study solutions.

Lynch (1990) is not optimistic about the increasing urbanisation of contemporary society. The satisfaction of the voracious urban metabolism transforms incoming resources into waste that is not compatible with the environment. Whereas, according to Wilmoth, Director of the UN's Population Division, progressive urbanisation, if regulated, could prove to be a positive factor both for economy and quality of life. Furthermore, the concentration of the population in large inhabited centres can help to minimise our environmental impact on the planet, optimising the location of resources, providing that administrations develop policies and practices to prepare for a huge influx of people (Meredith, 2018).

The meaningful contribution to the debate given by Rogers (2017) is remarkable. If we observe the latest transformations that have taken place in our cities, we will realise that probably, at some point in history, we have lost the ability to control the evolutionary processes of urban systems and the environment.

Theoretical evolutionary models of the urban metabolism as premises to parametric city design

The city can be defined as a constantly evolving metabolic organism, which self-regenerates by optimising its configuration over time according to the needs and availability of resources.

In 1826 Von Thünen deepened the first studies relating to the optimisation of the distribution of economic resources in a territory around a city. His work on the location of areas of agricultural land use (von Thünen, 1842) not only laid the foundations for a deeper analysis of the improvement of agriculture, but also stimulated interest in the location analysis of city resources.

Weber's model, by introducing variables relating to time and costs, and defining the minimum point of the cost of transport, attracting workforce and the agglomeration force of production factors, attempted to determine, in an isotropic space, the point where a production source must be located. The aim was to minimise costs and optimise the distribution of the product produced. Weber's analysis was very abstract. The formulation of an order in the spatial distribution of markets and cities, called "places", became the problem.

Christaller's model (Christaller, 1933) attempted to provide an answer, starting from the assumption that urban centres (central places) exist for the exchange or provision of goods and services to the population, spatially spread on a homogeneous and isotropic territory. Christaller presents the concepts of threshold and range that express in geographical terms the usual economic forces, which organise activities in space, the costs of transport and agglomeration economies, specifically the economies of scale.

Starting in the 1930s, Lösch (1954) began to update Christaller's model, treating the range, threshold, and hexagonal hinterland of each function separately. The resulting pattern is much more complex than Christaller's and yields a continuous, rather than a stepped distribution of population sizes (Fig. 2).

Parr's Comparative Statics Model (Parr, 1978) highlights how one of the fundamental forces of structural change in a territory is to be found in the technical progress and innovative processes that cause the blend of functions in urban centres. The size of its market area changes, until the disappearance of a well-defined hierarchical level.

In relation to the research on minimal path optimisation in an urban system, Rogers's studies on a small scale are remarkable, as well as his studies about circular urban metabolism (Rogers and Gumuchdjian, 1998) (Fig. 3).

Frei Otto (2011) elaborated some relevant thoughts on urban settlements and spheres of influence, referring to the eco-culture of a city and city analysis, including occupation of space and interconnections. Otto found analogies between aggregation processes that oc-

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cur in the natural world and forms of human settlements. Those archetypes are optimal models, as nature expresses itself and develops its phenomena with the minimum expenditure of energy (Fig. 4).

The contemporary latest paradigm can be defined as follows: city networks are sets of horizontal and non-hierarchical relationships between similar or complementary centres. This creates synergies and the formation of economies or externalities of specialisation.

Studies stimulated by contemporary urbanisation demonstrate how urban metabolism can be understood as a complex system of mutual relationships that a traditional urban planning approach cannot effectively drive. We should understand all the interconnected parts. Hence, the need for new planning tools. Parametric methodology, applied to urban planning, provides new tools to achieve this goal.

Parametric urban planning for the management of complexity

As illustrated, evolutionary processes of a city can be described by mathematical models that express organisational forms aimed at optimising complex processes of interaction between individual, community and environment. A further improvement in modelling urban metabolism followed the development of mathematical-statistical applications and computer science, which in those years began to be used in the analysis of economic phenomena. At the beginning, calculations were relatively simple; however, since the 1980s, the complexity of the models followed the development of micro-computing.

The development of computational tools in design had its cultural roots in studies conducted by Moretti (1954). He inaugurated studies on algorithmic urbanism, trusting in the potential offered by automatic computing. According to Moretti, a new architecture and a new urban planning process can issue only from the application of mathematical methods. This implies the analysis and study of mutual relationships of parameters to which reality can be reduced, intended as numerically expressible measures. In the late 1950s, Moretti argued about the possibility, which was innovative at the time, of applying Operational Research to urban planning. Operational Research, a methodology that aims to identify the most effective measures to achieve a pre-set goal through procedures based on mathematical and statistical concepts, consists of phases:

1. formulation of the problem;
2. collection and analysis of data;
3. construction of the mathematical model;
4. solving process of the mathematical model;
5. analysis and validation of the solutions obtained;
6. implementation of the solutions obtained.

The adoption of parametric tools in urban planning allows the definition of a new methodology that consists of a theoretical development of systemic models, whose formulation is based on the com-

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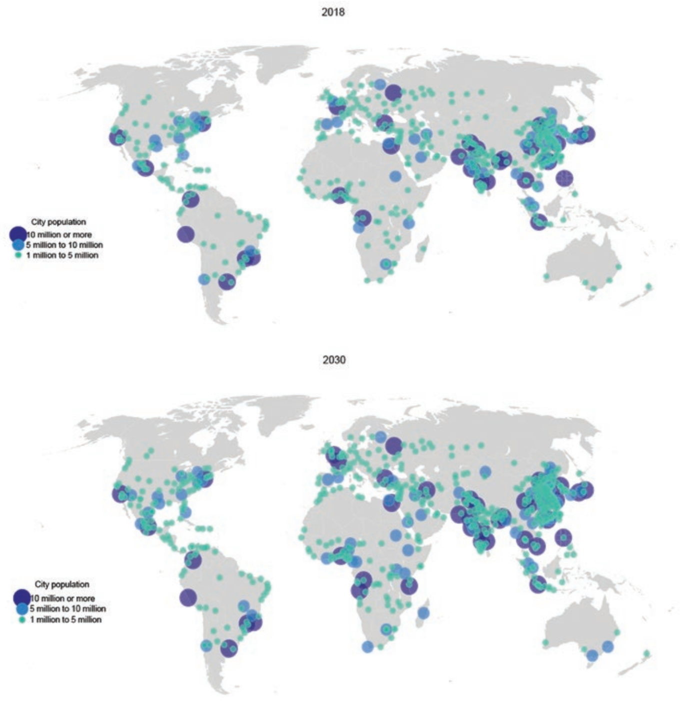

01 | Cities with one million inhabitants or more, 2018 and 2030 related scenarios (United Nations, 2018)

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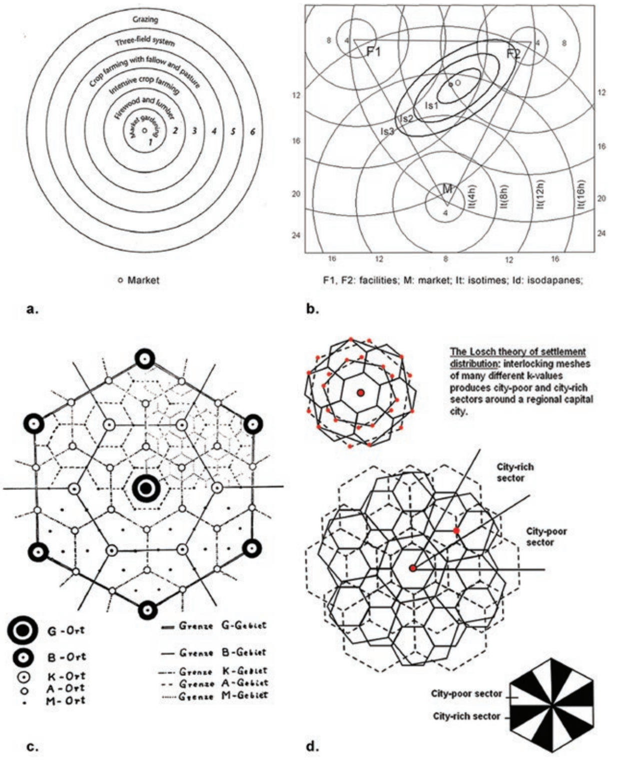

02 | a. Von Thunen's Concentric Model (Torricelli 2003); b. Weber's model (Torricelli, 2003); c. Christaller's model (Christaller, 1933); d. Lösch's model (Lösch, 1954)

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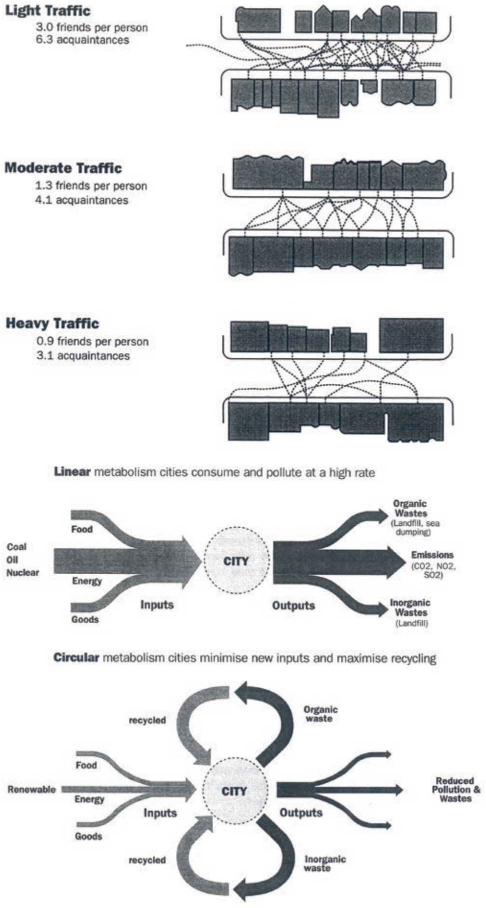

03 | Roger's studies on pedestrian minimal paths and urban metabolism (Rogers and Gumuchdjian, 1998)

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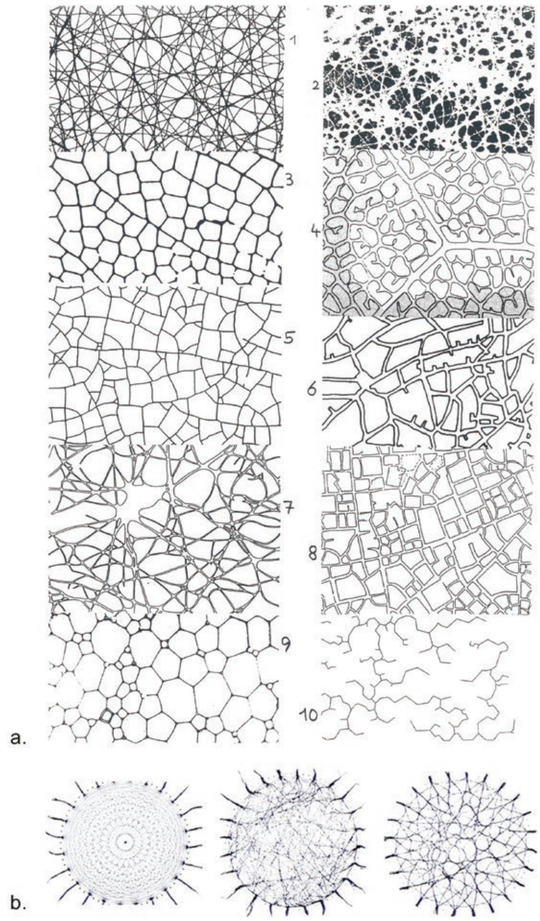

04 | a. Otto's comparative study on connection patterns in anthropic and natural environment (Otto, 2011); b. Otto et al., empirical studies of wool-thread on optimized path system (Otto and Bodo, 1996)

parison between urbanism and evolutionary processes. Through the propagation of its effects, the transformation of a single element, as parameters vary, can involve the modification of the whole organism.

Computational urban planning was successfully applied by Zaha Hadid in Kartal-Pendik masterplanning (Zaha Hadid Architects, 2006). Inspired by Otto's studies on path optimisation, this plan aimed at the redevelopment of an abandoned industrial site. An algorithmic script generates different typologies of buildings that respond to the mixed demands of each district. Through gradual transformations, the algorithmic script creates a smooth transition from the surrounding context to a new, higher density area. A masterplan is, therefore, a dynamic system able to generate an adaptive framework for urban form. It balances the need for a recognisable image and a new environment with a smart integration of a new area with the existing surroundings (Fig. 5).

In 2010 Carlo Ratti Associati and the MIT Senseable City Lab (Carlo Ratti Associati, 2010) developed the King Abdullah City for Atomic and Renewable Energy (Ka-Care) masterplan in Saudi Arabia. Focusing on algorithmic urban design, a code was developed. This could drive the evolutionary growth of the city, according to site-specific environmental parameters and design rules devised by planners (Fig. 6).

Overlapped City research by Remixstudio (2012) improves, through parametricism, urban energy efficiency, exploring the morphology of resilient post-fossil cities across three scales. These are the redefinition of urban boundaries and clusters, energy infrastructure framework and a new set of urban codes. The testing site is in West Houston, the fastest growing urban area in the US, with a rich potential for renewable energy production.

Digitisation, datafication and Big Data

Data corresponds to the Latin datum, whose meaning is 'something given'. Nowadays the word is regaining its original meaning.

Since the late 1950s, digitisation converted data from the analogue field of continuous values to the digital one of discrete values, translating them into a language decipherable by digital devices. It could be seen as the shift from atoms to bits (Negroponte, 1995). Digitisation has been crucial for data processing, storage and transmission. Datafication is a phenomenon brought out by the continuous development of ICT. It turns many aspects of our life into data and valuable information, going significantly beyond digitisation. Datafication, postulated for the first time in 2013 (Mayer-Schöenberger and Cukier, 2013), greatly exploits digitisation.

The meeting between datafication and digitisation generated Big Data, collections of data that were so extensive in terms of volume, speed and variability to require specific analytical technologies and

05 | Kartal-Pendik Masterplan: a. minimal paths infrastructural grid; b. urban tissue densification; c. parametric masterplanning outcome (Zaha Hadid Architects, 2006)

06 | King Abdullah City for Atomic and Renewable Energy (Carlo Ratti Associati, 2010)

07 | Proposed flowchart of Computation Urban Planning through Big Data Analytics

| 06

methods for the extraction of knowledge. Big Data refers to a leap in the interpretative paradigm of economic and social reality through analysis techniques (Data Mining and Data Driven) performed on huge volumes and 'varieties' of data, stored and processed at a fast speed, often in real time. The acquisition of Big Data has been made possible through the progress of digital devices and data transmission networks.

The spread of connected digital devices has changed the individual's attitude that voluntarily or involuntarily generates information. ICTs of the Fourth Industrial Revolution strengthened the relationship between physical reality and the digital world, attributing their own digital tracks to real phenomena and to human behaviours.

Big Data Analytics, evolution of traditional analytical methods, extrapolates, collects, analyses and correlates huge amounts of heterogeneous, structured and unstructured data provided by digital devices in order to extract latent information. It allows to perform predictive analyses based on Big Data. In fact, when huge amounts of historical data are available, one can foresee scenarios on statistical bases. Big Data Analytics consists of 6 Cs: Connection (sensors and networks), Cloud (computing and data on demand), Cyber (model & memory), Content/Context (meaning and correlation), Community (sharing & collaboration), Customisation (personalisation and value) (Lee, Bagheri and Kao, 2014).

Big companies of digital revolution commonly use the potential of Big Data Analytics to interpret and exploit the exceptional information contents of Big Data. The potential of this new analytical tool can be successfully used to drive adaptive and inclusive territorial policies.

Computational urban planning through big data analytics

The pervasiveness of sensors has outlined a new sector of use of technologies for the territory, namely City Sensing, which is joining the more consolidated one of Remote Sensing. City Sensing exploits small, miniaturised, portable or low-cost personal technological detection devices and their dissemination throughout the territory. An atomised and widespread technology appeared, changing the way a city is explored and used, i.e., inhabiting. The ability to virtually 'inhabit' multiple spaces simultaneously and in real-time thanks to the development of digital and connectivity systems allows to qualify and connote places in relation to one's habitus and needs, and to share experiences. The physical space is configured as a real substrate of a virtual and digital space of relationships, which is located on the Web and is characterised by its own rules and dynamics. This virtual space is the medium, which real individuals use to interact.

Hence, interconnected urban space is crossed by continuous data flows coming from a myriad of personal technological devices. Users, sharing georeferenced information, collected in first person, be-

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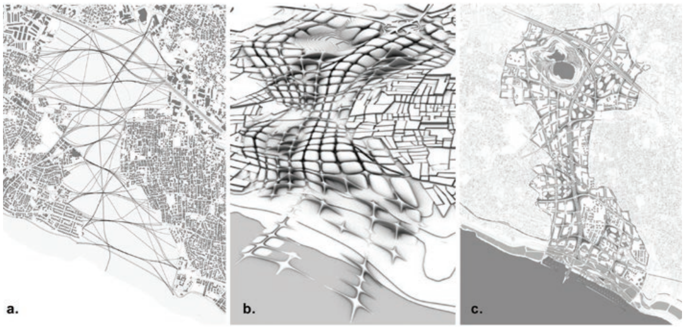

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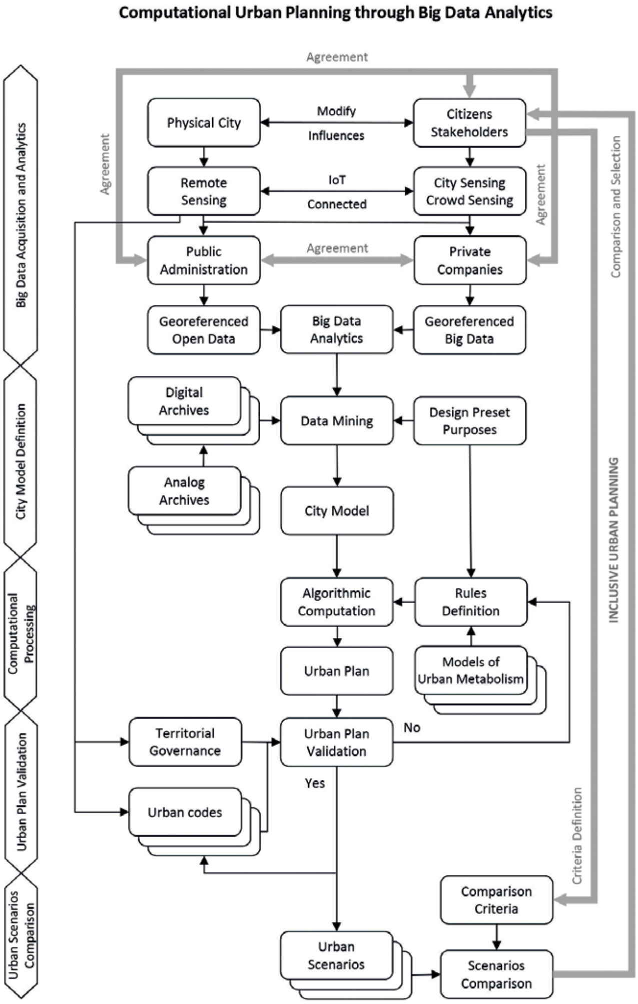

come themselves "sensors" of phenomena in progress. It becomes, therefore, possible to monitor complex phenomena that, otherwise, could not be observed (Resch, 2013). The need to effectively visualise data flows and those phenomena has pushed research into georeferenced data visualisation, which allows us to reach a deeper level of representation of urban phenomena. The City Model, new information model of a city, is digital, three-dimensional, multiresolution and in real-time. City Sensing and City Model mutually confer meaning and effectiveness, supporting multi-actor interaction and territorial governance processes.

As Borga claims (2013), the level reached by technology in the field of acquisition and processing of territorial data is significant. In public administrations, however, technical and cultural evolution has not taken place to the extent of fully exploiting that progress. The Open Government doctrine aims to provide open information to citizens for participating in decision-making processes. This can be achieved through sharing Open Data: information collected by the public administration and freely accessible to citizens. Open Data is a subset of Big Data but its purposes and uses are different. In fact, Big Data is mainly collected by private companies for business-related purposes. If Big Data were shared as a result of agreements among private companies and public administrations, it could considerably contribute to territorial governance.

The huge amount of Big Data, however, is unmanageable when applied to traditional urban planning methods still used by public administrations. Hence, Big Data Analytics can provide a crucial aid for information management and allow the development and the application of innovative multi-layer planning methods. Therefore, the convergence among the increased availability of data, Big Data Analytics, urban metabolism evolutionary models and computational tools can create a new urban design that goes beyond the limits of a traditional approach.

This new approach is Computational Urban Planning through Big Data Analytics, in which the inclusive and adaptive design based on algorithmic calculation exploits georeferenced data through a system of interconnected logical and mathematical operators. This methodology attributes control and validation to a human supervisor, giving the possibility to optimise results of the parametric calculation and to compare the different scenarios generated. A possible articulation of this methodological process could be the following:

1. acquisition and analysis of data;
2. definition of a City Model;
3. computational elaboration of the City Model (distribution of functions, density and massing);
4. validation and recursive optimisation of the results;
5. multi-scenario comparative analysis.

A flowchart (Fig. 7) exemplifies the methodology of Computational Urban Planning through Big Data Analytics using and updating a recent study (Galli and Massimiano, 2019). It also outlines a new methodological tool emphasising the central role of Data Analysis to create an interactive process that can reach urban design optimisation. The flowchart evolves the successful techniques adopted in the urban projects previously mentioned.

Conclusions

The last two centuries have witnessed the evolution and proliferation of various interpretative models concerning the development dynamics of a city and its territory. At the dawn of these studies, proposals focused on achieving the implementation of an ideal composition of political, social and, therefore, urban planning theories. Whereas in the latter half of the 20th century, given the stratification and increasing complexity of urban and territorial phenomena, knowledge of data from indicators, such as demographic, economic, and socio-cultural development, acquired increasing importance.

New technologies offer an extraordinary opportunity to improve the system of knowledge of the dynamics of behaviour, interaction and evolution of the natural and man-made environment. The disruptive diffusion of IT culture and, in particular, the proliferation of Web 2.0, have given voice (both in terms of expression of needs and information contributions) to local user groups initially excluded from top-down organisational models.

The possibility offered by these interactive technologies is able to adapt to the continuous evolution of the various levels of knowledge, which the professional investigation addresses, aimed at drafting local government models. For the first time in the history of Mankind, we act simultaneously both on the cognitive level and on the consequential response provided by the datafication this model produces. In analogy with building physics, it is as if this revolutionary innovation evolved the predictive capacity of the building envelope performance, analysed under static conditions, to the one, much more adherent to reality, analysed under dynamic conditions.

The application of a computational tool as a processor of apparently uneven Big Data Analytics opens up new scenarios. These will be both in terms of predictability of possible strategies that can be adopted and of on-demand responsiveness, generating an adaptive process, which can drive the transformations of a city.

The optimisation obtained through this process achieves the objective of controlling complex logic, such as the one proposed by circular economy models applied to urban metabolism issues. Likewise, it manages to involve, with a bottom-up process, even wider social strata aware of the processes of dissemination of the above-mentioned models and knowledge.

In these innovative processes and technologies lie possible contradictions between the role and the value held by datafication and data management, and the role of individual freedom and, therefore, of the individual citizen's ability to self-determine. The mutual acceptance of the boundary and its positioning, which can balance mutual interests and inalienable rights, encourages reflection on these issues towards a holistic approach and a multidisciplinary involvement of skills. These involve not only technical-scientific aspects but, equally, ethical-philosophical ones[1]. Nowadays, recent experiences in city regeneration, such as the Google Sidewalk Lab for the Toronto waterfront, confirm the effectiveness and the adaptability of this tool.

Therefore, without emphasising an optimistic and consoling horizon, trust is placed in the widespread diffusion and application of technologies for the implementation of a virtuous city and wise local government policies that make use of knowledge as an antidote to unethical exploitation.

NOTES

[1] Machine learning and computational design can help planners to generate not just a few but billions of comprehensive planning scenarios. Moreover, it can help to evaluate all kinds of impact these different scenarios could have on key measures for the quality of life, producing multiple options that best reflect a community's priorities. The generative design tool neither automates the urban planning process nor eliminates the need for human-driven design. Instead, it provides a set of features that can empower planning teams to do their job even better.

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