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Visualization Technologies to Support Decision-Making in City Management

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Abstract—Data is a valuable asset to the management of a city. With the growing integration of technology, some tools help collect, process, and visualize urban data, aiding the interpretation and understanding of how urban systems work. Despite the wide use of visualization to support decision-making in urban management, the understanding of urban data visualization in cities is limited in the current literature. In this paper, we propose a model of human decision-making supported by Information and Communication Technologies that helps understand the role of urban data visualization in city management. To analyze the use of visualization technologies in city management, we review the advances of information visualization to support decision-making in city management, and present a field study where we surveyed 35 government institutions to explore urban data and technologies "real use" in city management. Based on the literature review results and the field study, we identified the areas of opportunity for visualizing urban data to support city management.

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1. INTRODUCTION

In recent years, the world has experienced unprecedented urban growth. Today, half of humanity lives in cities, and it is projected to increase to 70% of the world's population in the next thirty years [1]. The increasing complexity of cities presents a challenge in managing resources and providing services. Faced with this scenario, urban data and Information and Communication Technologies (ICT) emerge as a critical component to optimize city's processes, activities, and services by providing key information to city decision-makers [2].

Current cities use computer tools to collect and analyze urban data to obtain useful information [3]. The analysis and interpretation of the gathered data can be difficult for a person's cognitive system [4]; for this reason, some tools integrate visualization to display information on their interfaces and facilitate their interpretation. Data visualization enables large amounts of data to be represented visually and meaningfully to enrich the analysis process, promote its understanding, observe relationships, detect patterns, and foster profound and unexpected insights [5, 6].

Data visualization is used in industry, government, academia, and other organizations to improve resource management such as land [7], water [8], energy [9], and cities' public administration [10]. Despite the wide use of visualization to support decision-making in urban management, the understanding of urban data visualization remains limited in the literature. Some authors, such as Kunze et al. [11], Singh, Wenzel, and Brettschneider [12], Pettit et al. [8], Batty et al. [13], explored the use of some visualization tools in cities, mainly in smart cities. However, none of these studies has summarized the current state of the art of visualization technology to support decision-making in cities.

Based on the literature review, Cepero and Montané-Jiménez [14] provided a general review of urban data visualization tools and their challenges to support decision-making in cities. However, [14] does not provide the perspective of users of this technology. This paper presents a comprehensive literature review of human decision-making supported by ICT that helps understand the role of urban data visualization in city management, and visualization technology used in city management. In addition to the literature review, this paper presents a field study where we surveyed 35 Mexican government institutions to explore the current use of urban data and visualization technologies in city management.

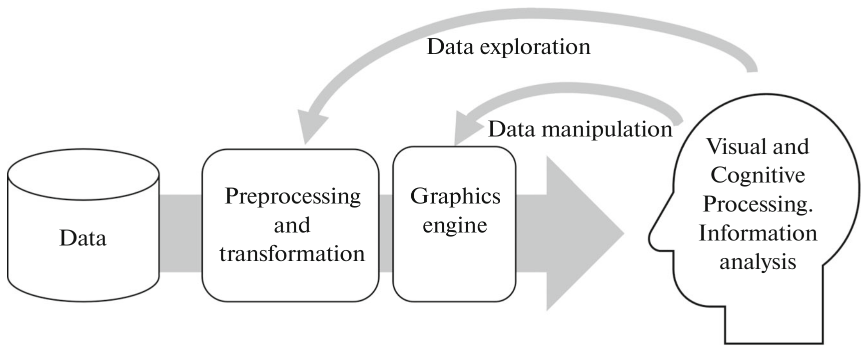

Fig. 1. Diagram of the visualization process [23].

This paper is organized as follows. Section 2 describes urban data visualization concept. Section 3 presents a model of the human decision-making process supported by ICTs that helps to understand the role of visualization technology in city management, in Section 4 we present a review of visualization technology to support decision-makers in cities, which includes a literature review and a field study. Finally, Section 5 presents conclusions and possible future work.

2. URBAN DATA VISUALIZATION

Urban data are a valuable resource for city management. Today's cities integrate instruments and many sources of information that make possible to measure and obtain large amounts of data on multiple phenomena, both natural and social [15]. A city's data is collected using traditional techniques and technology such as topography and photogrammetry, and advanced technology such as real-time sensors and satellites [16]. In addition to people and machine-generated data, processes, paperwork, business, and government transactions can be data sources [17]. These information sources provide massive amounts of data that can be extracted to facilitate a better understanding of how cities work [13].

The current infrastructure of cities enables relevant urban data to be collected, processed, and analyzed to understand the city's patterns, implement corrective actions, and address inefficiencies in urban space [18]. Although "real-time" information is indisputably valuable for understanding the current situation in a city, authors such as Carrera [19], Thakuriah, Tilahun, and Zellner [20], and Sharifi [21] also point out the importance of historical information. Complementing historical/static data sources with real-time data is likely to enable city decision makers to track changes more effectively and to facilitate a better-informed decision [21]. According to Carrera [19], a city can become a wiser city by connecting real-time big data with records from the past, and using it to model the future.

Increasing volumes of urban data are captured and become available. However, understanding and keeping track of the data generated in an urban environment is challenging [22]. One strategy to display urban data and facilitate its interpretation is visualization.

According to Card [5], visualization is "the use of computer-supported, interactive, visual representations of data to amplify cognition". The visualization uses visual and meaningful representations of data to facilitate its understanding [23]. Maps, bar charts, and scatterplots are common examples of information visualization representations.

The key idea of information visualization is to use people's powerful visual systems to process information that would otherwise require more cognitive effort [24]. The information visualization process (see Fig. 1) is developed in four stages: (1) Data collection and storage. (2) Preprocessing, at this stage, the data are transformed into something easier to manipulate; this regularly involves a process of data reduction. (3) Transformation of the selected data to a visual representation, this occurs through a computational algorithm that produces an image. (4) Perception, at this stage, the human cognitive and perceptual system receives the visual representation of the information [23]. According to Sacha [25], once the visual representation is perceived, the cognitive system analyzes the evidence, generates new knowledge, and relates it to existing knowledge.

The visualization model is split into two parts: (i) the part outside the person, in a computer system with data storage, processing, and visualization, and (ii) the human component where the cognitive system analyzes the information. The computer and human part are required for data analysis. Computers miss the creativity of human analysis that allows them to discover hidden connections between data and the problem domain. Humans are not able to deal efficiently with large amount of data. In visual analytics the connection between the human and computer uses the humans interaction abilities and perception [25].

Visualization is useful to increase our ability to discover information and generate new knowledge [25].

A good visual representation preserves the data - although sometimes it's important to represent relationships- and is effectively interpreted or its interpretation leads to fewer errors [5]. However, not all charts are useful and foolproof. During the visualization process, we can generate visual representations that cause interpretation errors due to a poor chart selection that does not fit the underlying data. For example, when the selected visualization technique does not serve to highlight patterns or trends in the data [26]. That is why the main challenge of visualization lies in finding a way to display information that maximizes understanding while minimizing the risk of misinterpretation [27].

Visualization and Analytics plays important role in decision-making in various sectors [28]. Due to the visualization's ability to show and facilitate the interpretation of large amounts of data, visualization has been used in urban contexts to facilitate the understanding of a city's data and obtain valuable information that supports decision-making.

3. HUMAN DECISION MAKING SUPPORTED BY ICT

A decision is the choice of an alternative or course of action. It is the result of considerations of facts and judgments that lead to a specific action [29]. A rational decision-maker considers the available information to analyze alternatives and chooses the one that is most likely to generate positive results for the person or organization, avoiding negative consequences [30].

Sauter [29] based on Simon (1977) defined decision making as a three-step process: intelligence, design, and choice. In the first step, intelligence, the decision-maker monitors the environment and identifies a problem or opportunity. The second step is designing. In this step, the decision-maker defines the decision, specifies the objectives to be considered, and identifies appropriate alternatives to the particular context. In the third step, the decision-maker considers the available information, compares the alternatives, and selects an option.

Shim et al. [31] conceived decision making as an iterative process of seven steps, which starts from the recognition of a problem and its definition. Shim et al. [31] suggest considering organizational, personal, and technical perspectives, in addition to ethical and aesthetic factors during the problem formulations. Once the problem is defined, alternatives solutions are created, and models are developed to analyze the alternatives. After the alternative analysis, the choice is then made and implemented. This model considers stakeholder mental models at the center of the decision process, from defining a problem to analyzing the alternatives.

Lau [32] proposed a "good process" of decision-making to obtain "good results". Lau [32] recommends: (1) think about how the decision should be made, (2) research relevant information, (3) make a list of options, (4) evaluate their pros and cons and select the best option, (5) prepare for possible contingencies, and (6) monitor progress and learn from the results. Although generating alternatives, evaluating them, and selecting one may seem like a simple process, the author acknowledges that one must be careful to obtain effective results. Conflicts can be generated in decision-making when there are conflicting objectives (unintended consequences), when there is uncertainty about the results, or when the person is unsure how to evaluate and compare alternatives [30]. According to Lehto, Nah, and Yi [30], conflicts occur when the decision-maker does not have a criterion (or decision rule) or enough information to carry out the evaluation.

Lehto, Nah, and Yi [30] proposed a model that integrates conflict resolution in the decision-making process. This model considers different sources of conflict, resolution methods, and results of conflict resolution in a decision-making process framed by a decision context. This model also considers mental models of problem-solving as relevant to describe human decision-making. They become especially relevant in the early stages of a decision where the problem is defined, options are formulated, and alternatives are analyzed [30].

The analysis of the decision-making models shows the importance of having information in the decision-making process. Today, thanks to ICT, we can obtain large amounts of data and generate information. The Miller and Mork data value chain [33] (see Fig. 2) proposes to manage data to create information that supports decision making. The first link in the chain is the data discovery link. This link involves collecting, preparing, and organizing the available data sources and the metadata that describes the quality of those sources. The integration link combines data into a common representation that suits a particular analysis. Once the data is integrated, in the exploitation link the data is analyzed and visualized. The goal is to provide stakeholders with meaningful information in an easy-to-consume format to make decisions [33].

The data value chain of [33] proposes a series of activities to gather data in an organized way and create valuable information that can inform decision making. In this model, decision-making is seen as a stage of information processing. However, as decisions become more complex, information processing becomes part of decision-making [30].

In complex situations, decisions can be difficult to formulate, and there is often no single correct answer or even no good alternative solution [29]. In response to these challenges, people use ICT to support the collection and analysis of information at different stages of the decision-making process. Based on the literature review [29–32, 34], we propose a model of the

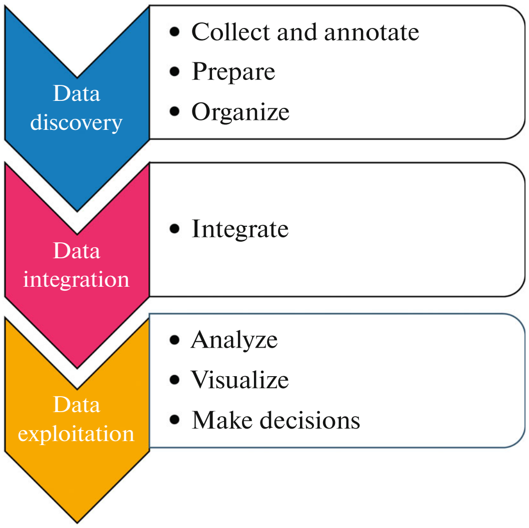

Fig. 2. The data value chain to create valuable information that can inform decision-making [33].

human decision-making process supported by ICT (see Fig. 3).

The model of the Human decision-making supported by ICT naturally involves human-computer interaction. The objective of the ICT component is to collect useful data for informed decision-making, facilitating its analysis and interpretation through visualization. The human component receives the information, generates an insight, and initiates a decision-making process to determine what actions to take.

The human decision-making process begins with monitoring the environment. In this step, the decision-maker obtains information from the environment through ICT use. Based on the information available, the person evaluates the situation using organizational, personal, or technical criteria [31]. This situation assessment could lead to the recognition of a problem. The next step is to define the problem by analyzing the available information and defining the problem more precisely. For example, a person monitors the city traffic and identifies a region with more traffic than usual; at this point, the person will analyze information from the region -such as traffic accidents- to evaluate the congested streets and propose travel alternatives.

Once the person identifies a problem, appropriate alternatives are identified to achieve their goals in a decision context (doing nothing can also be considered an alternative) [30]. This step generally includes collecting information, elaborating alternatives, and examining the factors that could influence the viability of the proposed alternatives [29]. In the next step, the person analyzes the alternatives and selects one. In these stages, the availability of information and the stakeholders' mental model plays a key role in the decision process, from the definition of a problem to the analysis of alternative solutions to solve the problem [31].

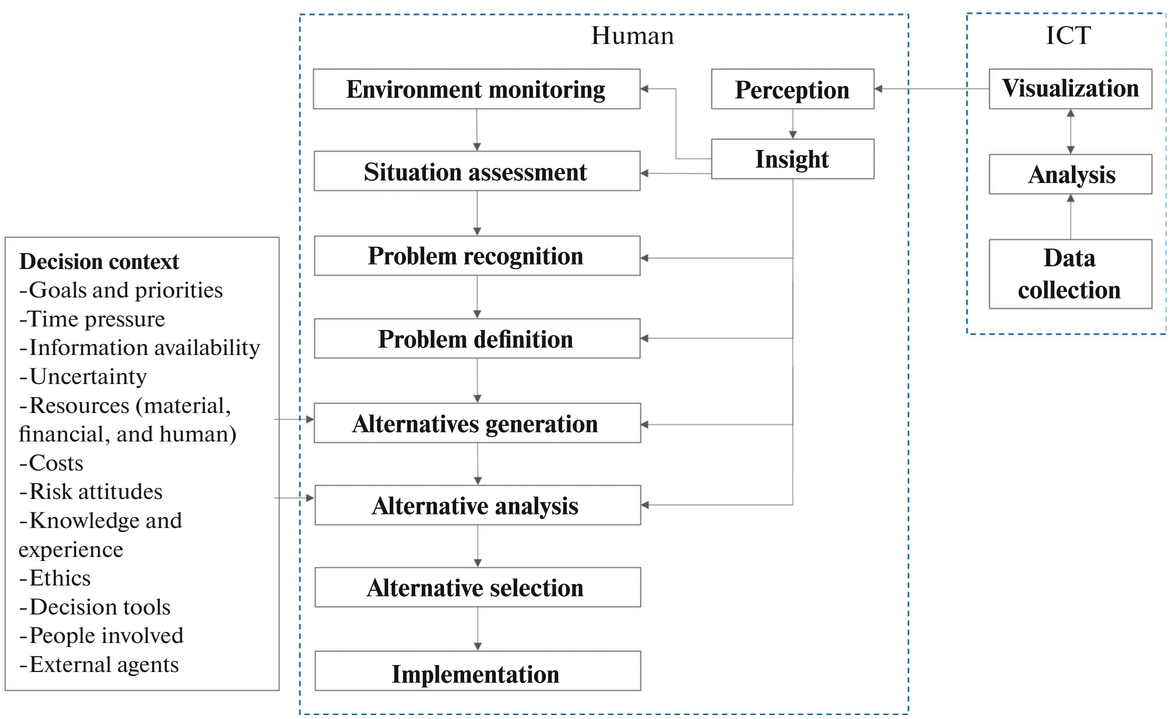

Fig. 3. Human decision-making process supported by ICT.

A rational decision-maker compares the alternatives and evaluates them based on an appropriate criterion or rule to make decisions that generate desirable consequences and try to avoid undesirable effects. The alternative analysis is a process in which a person rates or assigns values to the alternatives' attributes. For example, Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis and pros and cons analysis are popular techniques for analyzing alternatives. Some common evaluation criteria are aspirations, importance, preferences, and probability of success; On the other hand, the best-known rules or axioms for decision making are the principles of subjective expected utility and the rule of maximizing expected utility. The selection of the analysis technique, criteria, and decision rules will depend on the priorities, the context, and the objectives [30, 32].

In organizations, different people participate in the activities of strategic planning (executive decisions regarding the mission and general goals), management control (intermediate management that guides the organization towards specific goals), and operational control (supervisors who direct specific tasks) [31, 35]. Therefore, even within the same organization, the problem can be approached from diverse perspectives since people have different objectives and priorities, leading to different decisions and information needs [35].

Decision-making varies depending on the decision context. Decisions can be informed or in uncertain situations; they can also be made under time constraints and involve consequences of different magnitudes, from trivial to catastrophic consequences. The availability of resources can restrict or influence choices. Decisions can be made by a single person or by a group. Within a group, there may be conflicting opinions and different degrees of power between individuals. Decision-makers can also vary widely in their knowledge and degree of risk aversion [30]. The outcome of the elections can be determined by external agents such as cultural, personal, ethical, aesthetic, organizational factors, among others [31]. In addition to the contextual elements that affect decision-making, people may have unintentional cognitive biases that deviate judgment from rational decision-making, usually negatively impacting decisions [25].

Given the variability of the mental models of decision-makers and the complexity of the decision-making process, challenges arise from the participation of humans as decision-makers: conflict resolution in collaborative decision-making, subjectivity, bias, the choice of metrics to evaluate decisions, and the evaluation of the effects of a decision [34].

The effectiveness of the ICT-supported human decision-making process strongly depends on the integrity of the information and how the data is presented [36]. In addition to possible human analysis errors, there can also be problems with data manipulation. Failure to detect these problems can lead to wrong analysis and false discoveries. As Miller [33] points out, "It is naive to think that simply connecting data will reveal your wisdom. Low-quality data will not produce useful results, regardless of how smart the integration, analysis, or visualization may be". It is also important to consider the relevance of the data and avoid presenting information that is not relevant, or imprecise for the user. For this reason, it is important to take care of the data integrity, the relevance of the presented information, the reliability of the analysis, and the usability of the visualization [33].

The power of human decision-making supported by visualization technology comes from the "effective delegation of cognitive reasoning, domain knowledge and decision-making on the human side, and computing and data storage capability on the machine side, and their effective coupling via visual representations" [25]. Therefore, visualization technology is a valuable aid to support the evidence-based decision-making process.

Visualization technology helps connect government decision-makers with the information needed to make strategic and operational decisions, such as emergency management and long-term strategic decisions in city growth planning [8]. Decision-makers and planners increasingly use an evidence-based decision-making approach to achieve more efficient results. According to this purpose, visualization technologies could be considered the main tool to support city managers [37, 38].

4. REVIEW OF VISUALIZATION TECHNOLOGY TO SUPPORT DECISION-MAKERS IN CITIES

Effective city management requires an evidence-based decision-making process to achieve optimal results. Throughout the decision-making process, stakeholders can use different data collection, transmission, processing, and visualization technologies [39].

A visualization system (see Fig. 4) is a software that allows the user to select, process, and present data visually [40]. Through visualization systems, decision-makers generate ad hoc visualizations that facilitate data exploration and make inferences from the information displayed, which can lead to useful findings to solve an analysis task [25].

According to the knowledge generation model for visual analytics of Sacha et al. [25], the interaction with the visualization system and inferences is carried out continuously through cycles in which people explore the data in a non-deterministic but spontaneous way. Users can frequently change their exploration strategies and switch between visualizations to collect different findings [25].

Users of interactive visualization systems explore data by interacting with its interface and observing the

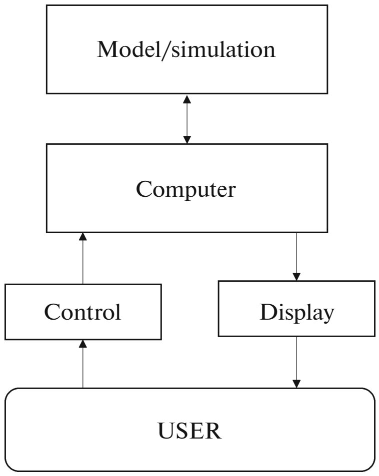

Fig. 4. Manual interactive visualization system [40].

resulting output [25]. The design of each display system and its interface will depend on the scenario. However, according to Card, Mackinlay, and Shneiderman [5], a basic principle for this type of system is to support the elementary tasks for the visual exploration of information: the general description (overview), zooming, filtering, and consulting details upon request. These functions are a starting point; the system can support other tasks that might be desirable depending on the scenario [5].

This paper presents a literature review accompanied by a field study that shows the current use of urban data visualization technologies in city management. We performed a literature review based on Kitchenham guidelines [41] to identify the advances in visualization to support decision-making in cities, the technology used, and the challenges and opportunities in the field.

The systematic literature review was performed in four steps: (1) resource identification, (2) selection, (3) data extraction, and (4) data analysis.

To identify the resources, we used the keywords “data visualization, information visualization, decision support, decision making, city, urban” to construct three search queries by connecting the synonyms and different spellings. We used the queries in five research databases: ScienceDirect, IEEE, Springer, ACM, and Wiley. The search was done for titles, keywords, abstracts, and body of documents, without any specified time range. The results of the query Q1 were 37651 papers, 24005 papers for Q2 and 50471 papers for Q3. This adds up to 112127 identified resources, of which a sample of 2835 was taken using the MIL-STD-105E sampling scheme.

As Fig. 5 illustrates, from the 2835 papers in the sample, a selection assessment was made of the resources that provide relevant information on visualization technology to support city management decision-making. The selection of papers was made based on the inclusion and exclusion criteria shown below:

Inclusion criteria

(1) Research related to information visualization to support decision-making in cities.

(2) Publications of journal papers, book chapters, and conference proceedings.

(3) Documents in English or Spanish.

Exclusion criteria

(1) Research not related to the visualization of information as a support tool in cities.

(2) Repeated papers.

The article selection process was carried out in two iterations. In the first one, the papers in the sample were examined against the inclusion and exclusion criteria based on their title; 168 articles were selected from the 2835 articles identified. In the second iteration, 64 relevant papers were selected based on an analysis of the abstract and full text of the selected papers.

After analyzing the 64 selected papers, we identified the advances in visualization to support decision-making in cities, the tools used, and the areas of opportunity in the field.

4.1. Advances in Visualization to Support Decision-Making in Cities

Cities integrate different systems -such as transport, energy, water management, etc.- enriched with ICT. The literature review revealed that cities collect data from these systems to monitor activity and resource use in the city. The aspiration of the city of the future is to collect and analyze urban data in real-time, from which local authorities can visualize the city’s activity and make better evidence-based decisions [8, 42].

In the last decade, research and information visualization projects for cities have advanced thanks to the evolution of ICTs and development efforts carried out by academia, the government, and the business sector. As Batty et al. [13] and Barns [43] point out, IT companies, such as IBM and Cisco, focus on developing systems and sensors to collect data of the city’s operation and analyze it in real-time to monitor and control public services. According to Barns [43], this commercial technology is a product designed to be attractive to consumers – largely government agencies- and generate profits for companies, which does not provide the necessary support to face the challenges of a city.

Governments and local authorities also played an important role in the development of visualization technology to support decision-making: as developers of technology to meet their local needs, and as open data providers to encourage external users to design public digital services, like the London government

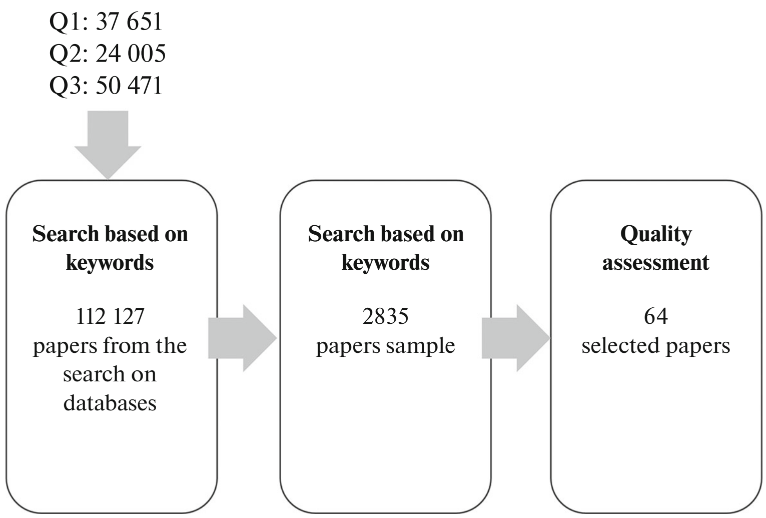

Fig. 5. Procedure for selecting primary studies.

that provides open data that feeds the public dashboard "City Dashboard" developed by University College London's Center for Advanced Spatial Analysis (CASA) [43].

The academic community, in addition to develop systems, has contributed to the development of a body of knowledge on information visualization in cities. For example, analysis of data use cases in smart cities [44], analysis of preliminary specifications for visualization tools to support transportation planning [45], identification of good visual communication practices for sustainability performance assessment [46], identification of challenges and considerations [27, 44, 47], a proposal of guidelines for the design of visualization [48], a model for a city's dashboard [49], investigation of visualization technological environments [8, 12, 13, 43] and tools to support decision-making in urban management [11, 15, 16, 43] apps development [11, 19, 50–53], among other contributions. Analyzing these advances, we present a review of visualization technology and the areas of opportunity in the field.

4.2. Visualization Technology

Based on the literature review [8, 11, 13, 43, 54], we identified eleven visualization platforms that are widely associated with exploration, analysis, and visualization of urban data. The following list presents the visualization technologies used to support decision making in cities [14].

Data repositories store and provide access to open data. Data repositories can also be found under names such as open data portals, marketplaces, warehouses, or datastores. Although this platform is not focused on information visualization but on data access, these platforms use visualization to organize data and make it functionally available [43].

Digital Globes provide interactive visualizations of the planet, as well as the cities and spaces that comprise it. These digital viewers allow exploration of photorealistic structures and phenomena from the real world, supporting the visual understanding of geospatial relationships in the environment [8].

Geographical Information System (GIS) and Cartography Tools are used to manage geo-referenced information. With the ability to overlay data sets, spatially filter them, and make geographic analysis, GIS makes it easy to compare scenarios and support urban professionals in decision making. Therefore, in an environment where spatial analysis are relevant, interfaces with GIS functionalities are highly desirable [8].

Virtual Simulation Environments (VSE) represent urban space in three dimensions. VSE allows photorealistic representation of physical and environmental objects and dynamic phenomena such as traffic and weather with movements that simulate behaviors. Using VSE, decision makers can simulate real-world aspects and try different scenarios [8].

Building Information Models (BIMs) represent detailed construction models. The BIM model is a digital prototype of the physical elements of a construction project, such as pipes, walls, doors, etc. that simulate the building and its behavior. In addition to building simulation, they are used to store and manage project data, such as area, materials, budget, etc., which allows users to understand building performance and design [8].

Game Platforms (or game engines) are computer programs for creating video games that, thanks to the tools to make high-quality 3D representations, are being used to represent urban projects. Game platforms also offer high interactivity and portability. This technology allows, for example, to walk through a project or city and interact with its elements [8].

Data portals show public city information. Census and geographic information portals, such as the Statistics and Geography of Mexico (INEGI), are examples of portals that use visualization techniques to consult and display information of a country or city [13].

Spreadsheets are a tool to store data, analyze information, and generate visual representations such as line charts, bar charts, pie charts, among others. This platform offers even more data analysis and visualization tools, making it possible to develop models within a spreadsheet and link them to other graphic media [55].

Decision support systems (DSSs). The goal of the decision support system is to help people make better decisions and more easily [11, 29]. There are also specialized systems to support planning decisions. The Planning Support Systems (PSSs) are tools dedicated to support planning processes or parts thereof. PSS pays particular attention to long-range problems and strategic issues, while DSS is designed to support shorter-term concerns and policy-making [56].

Dashboards are a visual display used to monitor at a glance the most important information needed to achieve one or more objectives [57]. Dashboards are characterized by access to linked services, which we can use to monitor information and measure performance [43]. Thanks to their ability to display information in an accessible way, dashboards have been adopted to monitor urban space activities.

Smart city platform collects and analyzes large-scale data to monitor city operations. These platforms can also be coordinated with other systems or applications that activate, automate, and control other urban elements or subsystems. The smart city platform systematically collects data at intervals of several seconds to several minutes, cleans and analyzes the data, and displays useful information for local authorities and service providers [3].

Urban data visualization technology helps to obtain and communicate information that support decision-making in city management. For example, dashboards are a technology designed to facilitate information monitoring; therefore, they are naturally helpful in monitoring a city. Spreadsheets are the most used tool to store information, analyze it, and generate visual representations such as scatterplot, bar chart, pie chart, among others [55]. With its advanced geographic analysis, GIS technology is useful for evaluating the situation in urban space and analyzing alternatives by comparing scenarios.

According to Viale [38], using ICT, such as GIS, open data portals, and others, promotes data-based decision-making. For example, government agencies use data-based spatial analysis when estimating the spatial scope of natural disasters. On the other hand, when analyzing industrial risks, it is a good practice to model the impact of an accident and see the possible effects. In addition to spatial analysis, visualization with statistical graphics is also widely used in city management, for example, in the analysis of the key performance indicators of each institution.

The visualization technologies mentioned above help to support the diverse needs of city decision-makers. The literature review shows that this is just the beginning of visualization technologies, not only because these platforms will improve with new technological advances, but new platforms are emerging that integrate the best of different technologies, such as spreadsheets with GIS functions to make spatial analysis, or BIM with Game Platforms to analyze construction projects from different perspectives thanks to virtual reality and augmented reality. Although novel urban projects are developed with virtual, augmented, and mixed reality systems, there are still ergonomic challenges to overcome the discomfort of visual perception of its use [58].

The literature review shows that there is currently a wide range of visualization tools that can be used in city management. However, in the everyday reality of city management, decision-makers do not necessarily make use of all available tools. We surveyed government institutions in México to analyze the experience and preferences for the use of urban data and visualization technologies in city management.

4.3. Field Study

We conducted a field study to explore the use of ICT in city management. This research aimed to collect information about the information sources used in city management, to understand why city managers use the selected information sources, what they use the information for, and what visualization systems they currently use.

The information was collected by applying a virtual questionnaire to the government authorities through the transparency platform (www.plataformadetransparencia.org.mx). For this study, we took a sample of 35 government institutions of the three levels of government in Mexico: 10 federal institutions, 15 state institutions, and 10 municipal institutions from different states. The selected institutions cover different fields of public city management: economy, infrastructure, administration, agriculture and rural development, social development, energy, security, tax collection, environment, transportation, employment and training administration, education, culture, and general government.

Table 1 shows the results of the information sources used in the interviewed institutions. The results show that the main source is the information generated within the institution's operations, followed by information from other institutions and the National Institute of Statistics and Geography (INEGI for its acronym in Spanish). The institutions also indicated the use of institution's systems and publications from

Table 1. Information sources used in the surveyed institution

Governmental institutions	Sensors	Institution's systems	Information from the operations of the institution	National Institute of Statistic and Geography	Other institutions	National/international organizations	Other
Federal (10)	0	4	9	7	9	6	1
State (15)	0	10	12	10	12	9	3
Municipal (10)	0	6	9	7	5	3	4
Total	**0**	**20**	**30**	**24**	**26**	**18**	**8**

national and international organizations. Among the 29 organizations mentioned, the United Nations (UN), the World Bank, the Official Gazette of each state, and the National Electoral Institute stand out. They also reported using other sources of information, and the most used was the local, national, and international press.

Regarding the reason for using the information sources, the surveyed institutions reported 18 different reasons – some indicated more than one reason. As Table 2 shows, 8 of the 35 surveyed institutions (23%) said that they use the selected sources because these are necessary for the institution's functions/activities; 7 institutions (20%) use them because they are official sources of information; 6 institutions (17%) use the selected sources because they are trustworthy/reliable; 3 institutions (9%) use the sources because provide reliable and updated data; among other reasons.

The surveyed institutions reported that the main uses of the information consulted are: for the development of their functions/work/activities; to make reports; generate information and statistics; to provide the population with relevant information; for planning; for the fulfillment of the institution's objective and goals; To support decisions; perform analysis that helps decide the best actions; for the planning, design, implementation, and analysis of public policies; for the monitoring and evaluation of programs and projects; and the measurement of results.

Regarding the current use of specialized computer systems (see Fig. 6), 33 of the 35 institutions surveyed (94%) reported using spreadsheets, 29 institutions (83%) use their institution's systems, 23 institutions (66%) use data portals, 22 institutions (63%) use data repositories, 16 institutions (46%) use digital globes – mainly Google Earth-, 12 institutions (34%) use CAD, 11 institutions (31%) use GIS, 9 Institutions (26%) use dashboards, 4 institutions (11%) use smart city platforms, 2 institutions (6%) use BIM, and 19 institutions (54%) reported the use of other specialized systems. From this last category, 35 different systems were indicated, of which stand out the development tools for web and desktop, and the accounting, payroll, and budget systems for their use in multiple institutions.

Finally, only 30 institutions answered the question, "In case of using a specialized system or program, what do they use it for?" Of which five institutions (17%) responded that they do not use specialized systems. However, these same institutions also reported having used spreadsheets, data warehouses, and data portals, and in some cases GIS and CAD. As shown in Table 3, the respondents indicated that they mainly use specialized systems to perform the activities and operations of the institution, design and implement public policies, and provide attention to citizens who request service. They also indicated the use of specialized systems to collect, analyze, and visualize information.

This field study helped identify the main uses of specialized systems in a sample of public institutions in Mexico. However, this study also showed that different areas can develop different activities inside an institution and use different systems; As one surveyed institution pointed out: "the use of the systems varies, each agency uses the information depending on its needs and services".

The results of the field study show that the surveyed institutions generate and use information from their activities, as well as information published by other institutions and organizations. Local authorities con-

Table 2. Reasons why institutions use the indicated information sources

Reasons for using information sources	Number of institutions
They are necessary for the exercise of the functions/activities of the institution	8
They are official sources of information	7
They are trustworthy/reliable	6
They are reliable and up-to-date data	3
Allow to follow-up in a timely manner	2
Serve to analyze performance	2
They are the sources that provide the information they need	2
They are agile and efficient	2
Other	10

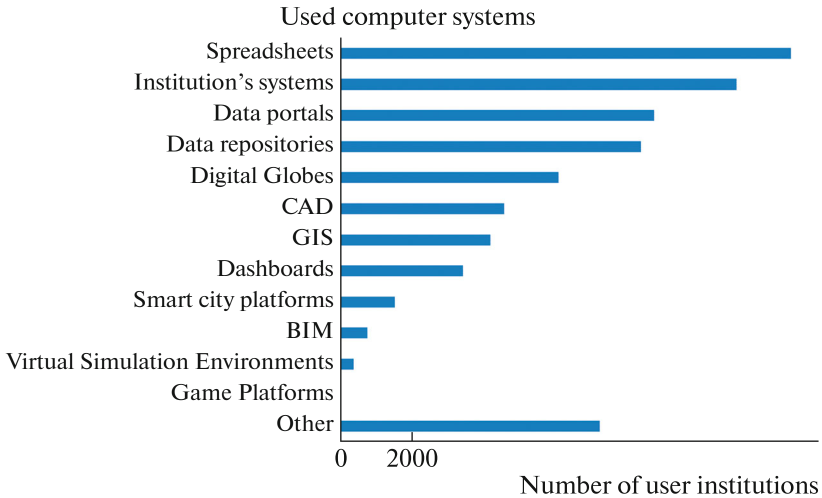

Fig. 6. Currently used specialized computer systems.

sume internal and external information to develop projects and public policies based on evidence. These findings highlight the relevance of information and data analysis tools in city management.

4.4. Challenges and Opportunities

This section provides a brief discussion of the challenges and opportunities identified in the literature and the field study. Table 4 summarizes the main challenges and risks in urban data visualization technologies.

The literature analysis shows challenges and risks at different stages of the visualization process, from data collection to the interpretation of the visual representation. In the data collection stage, it can be challenging to collect data from different sources, manage data heterogeneity (from text to video), low data quality, exchange information between different systems and devices, and lack of testbeds to develop and evaluate visualization technology. During the data processing stage can be challenging to pre-process data with the above characteristics and analyze it to obtain useful information. At the visual presentation stage, it can be challenging to select a visual representation and to work with pre-defined static views. In the perception stage, the main risks are information misinterpretation and difficulty making decisions.

We also identified technology design challenges related to the difficulty of use, low usability, and lack of user participation in the design. Additionally, there are some general challenges of data privacy, security, scalability, and maintenance of the platforms. Considering that many city management decisions are made within an institution, there are also some organizational challenges to consider, such as lack of trained personnel, training costs, high costs of professionals, lack of resources, and unclear vision of the ICT management.

Table 4 presents a summary of the general challenges and risks of visualizing data to support city management. However, each technological tool has its challenges. Geertman and Stillwel [56] analyzed the use of Planning Support Systems (PSS) and bottlenecks in their implementation and use. The study points to a difference between what potential users need in practice – a simple and straightforward system for routine tasks – and systems supplied by developers according to their perceptions of what is required – advanced systems focused on more analytical tasks [56].

The demand for simple systems and the supply of advanced systems, what Pettit et al. [16] calls the

Table 3. Specialized systems application purposes

Application purposes	Number of institutions
Does not use specialized systems	5
To perform the operations or activities of the institution	4
Planning, design, budgeting, and policy analysis	3
Provide attention to citizens who request a service	3
Statistical analysis	2
Capture and process the information generated	2
Consult, analyze, and visualize information	2
Get information	2
Payroll processing and asset control	1
Other	6

"implementation gap", has led to problems such as lack of utility, lack of intention to use PSS, lack of ease of use, among other issues [56]. In another study on the use and adoption of PSS in urban planning, Russo et al. [63] also points out the limited use of PSS caused by the unfulfillment of user needs and low usability.

The implementation gap is not a problem exclusive to PSS, other visualization platforms such as virtual simulation environments and gaming platforms are also difficult for users to manage [12]. Many dashboards have also failed, not because they are difficult to use, because their design focused on data and not consider users' functional and information needs, which often ends up in non-functional products. In addition to usability challenges, Matheus et al. [59] also points out as relevant challenges in dashboards: insufficient data quality, lack of understanding of data, poor analysis, wrong interpretation, confusion about the outcomes, and imposing a pre-defined view.

In a study that integrates the experience of developers of environmental decision support systems, McIntosh et al. [64] offers a set of recommendations and good practices to solve the challenges of engagement and technology adoption. The best practices suggested to overcome the challenges include: designing for ease of use, designing for usefulness, and establishing trust and credibility. To achieve these goals, McIntosh [64] recommends design based on a good understanding of user expectations, needs and behaviors and evaluated with regards their specific utility and benefits to different users. Similarly, Young et al. [65] recommends improving the design of city dashboards by taking into account users' expectations and skills in the design process. The study recommends the user-centered design (UCD) approach to improve the usability and usefulness of city technologies in general.

According to the UCD framework [66, 67], visualization technology should consider the data meaning, the user characteristics, the task context, and the visualization methods features to select the representation that facilitates interpretation [27, 67, 68]. The consideration of these elements in the design process will favor the optimal visualization of urban data.

With the application of the UCD approach, other challenges may arise related to identifying users, their recruitment, possible difficulty in establishing contact, communication, and getting feedback in the development process. Once end users have been identified and engaged, developers may have difficulties in successfully extracting the required information if they do not perform an adequate analysis or if users have difficulties expressing themselves [64].

Grainger, Mao, and Buytaert [69] synthesize best practices from multiple disciplines that serve as guidelines for applying user-centered design to visualization systems design. However, although they help guide the design process, these general principles lack the necessary details to implement them successfully.

Table 4. Risks and challenges

Dimension	Risks and challenges	Authors
Data collection	• Data collection	[9], [30], [48], [55]
	• Low data quality	[34], [59]
	• Heterogeneity of data, devices, and applications	[34], [60]
	• Data integration	[27], [45], [61]
	• Data-exchange	[61], [60]
	• Lack of Testbeds	[60]
Data processing	• Preprocessing	
	• Data analysis	[8], [34], [53], [60], [62]
Data presentation	• Data visual representation	[27]
	• Pre-defined view	[52], [59]
	• Lack of visualization guidelines	[46]
Design	• Difficulty of use	[3], [16]
	• Low usability	[58]
	• Lack of user participation in the design	[11]
Persons	• Misinterpretation of information	[27], [59]
	• Decision making	[8], [15], [51], [59]
Organizational	• Limited knowledge and no suitable staf	[59], [61]
	• Lack of resources	[61]
	• Unclear vision of IT management	[61]
	• High cost of IT professionals and consultancies	[61]
General	• Data privacy	[34], [59], [60]
	• Security	[34], [60]
	• Scalability	[60]
	• Platform Maintenance	[60], [59]

The field study shows that utility is the main criterion in using urban data and selecting technologies. Most of the surveyed institutions revealed that they use ICTs because they help them perform the institution's operations and activities. These findings are consistent with McIntosh's study, where he notes that technology adoption increases when systems help people solve problems or perform tasks more easily. We have limited information on the problems faced by decision-makers in urban management and how they currently solve them; this information is necessary to guide technological developments to the real needs in city management. Therefore, more field studies are necessary to analyze the decision-makers profiles, experiences, and opinions to push forward our understanding of visualization technology use and potential.

All the identified challenges in this review require careful consideration and present practical challenges. Urban data visualization technologies should focus on the person not only at the level of representations, as is often the case in many visualization products, but also at the levels of data, tasks, and functions [67]. Therefore, next-generation visualization platforms should be equipped with new features, functionalities, and facilities that allow the integration of user preferences and priorities for the generation of knowledge.

6. CONCLUSIONS

We proposed a model of human decision-making supported by ICTs that helps to understand the role of visualization technology in city management. We also analyzed the technological advances of urban data visualization and the challenges in the area. From the literature review results, we found eleven visualization technologies widely used for the exploration, analysis, and visualization of urban data. Regarding the challenges in urban data visualization, the literature suggests that information visualization to support city management's decision-making remains limited in theory and practice. The offer of visualization technologies that do not consider the users and their real needs has led to low acceptance of the technology. To address these challenges, some authors propose using the User-Centered Design approach in urban data visualization design to select the representation that facilitates its interpretation and favors insight.

We also carried out a field study that allowed identifying the main sources of information in 35 government institutions, what authorities look at in the selection of information sources, and what tools they use. We found that the main attributes that local authorities look for in the information are usefulness (for their activities) and data reliability. Interestingly, the most popular tool used by local authorities is spreadsheets. We do not know why spreadsheets are the preferred tool, but it would be interesting to analyze what makes this tool so attractive and perhaps extract some lessons that can be used to design other tools.

Our study presents a literature review accompanied by a field study that shows the current state of the use of urban data and visualization technologies in city management. Although these technologies have been previously explored [14], our principal focus was understanding its use in theory and practice and identified the challenges of developing more useful and usable systems for city management. The usability challenges identified require integrating different disciplines, such as HCI and information visualization applied to urban management. Therefore, it would be desirable to design guidelines and frameworks that help integrate these disciplines in urban data visualization design. Thus, we encourage future studies to address these challenges to improve specialized technology for urban data visualization.

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