Towards the creation of a searchable 3D smart city model

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Abstract

Purpose – This paper aims to create a new searchable 3D city model to help managers improve their decision-making.

Design/methodology/approach – This paper identifies data management basics and the key elements used in the new model design; it further analyzes five-city models, presents its findings and proposes analytical trends for the new model. It discusses the concepts underlying existing models, explains the benefit brought by the proposed model and demonstrates its robustness.

Findings – City systems can be interconnected, thanks to data digitization and the integration of new technologies into different management processes. Although there are several 3D city models available, none of those identified in this research can be queried for several sectors.

Research limitations/implications – This model design can only be successfully realized in the presence of a public mandate. Potential limitations include information security risks and political non-acceptance.

Originality/value – The present work proposes a searchable and high performance model having the distinctive capacity to bring together city systems and perform real-time data analysis in order to extract important information needed to guide the city, and in the context of a global vision.

Keywords 3D city model, Digital model, Data management, Blockchain, IOTA, Smart city, BIM, SIG, CIM

Paper type Literature review

1. Introduction

A city is a system of systems (Wu et al., 2018). City systems can typically be classified under four categories, namely, population, government/municipal authorities, territory and infrastructures (Dameri, 2014):

> Worldwide, there are over 3.3 billion people living in cities. Presently, while cities take up barely 2 per cent of the earth's surface, they are home to 50 per cent of the world population, consume 75 per cent all the energy produced, and are responsible for 80 per cent of all CO_2 emissions (Soucy, 2016).

In terms of city management, decisions are made in the context of challenges, which are not only economic, social and environmental but which can also be in the form of often competing and conflicting interests among managers. A review of a few management

strategies, processes and types allowed us to observe and identify the limitations inherent in existing management domains: low digital and technological maturity; lack of a strategic vision for sustainable development; problem resolution limitations, and the emergence of new problems; *silo* management; scope of human resource and change management; and the importance of managing and owning data.

In the face of issues that are constantly increasing in scope and complexity, the solutions proffered to aid in decision-making are also becoming ever smarter. These include, for example, the blockchain, building information modeling (BIM), Geographic Information System (GIS), the smart city and digital 3D city models. All these solutions are based on data and rely on technology, which explains the need to review the literature on all of them and to understand how to use existing databases when designing the city.

Data centralization raises certain concerns in terms of their control, security and ownership. Financial institutions, for instance, consider data and transaction security as a critical issue. Some use the blockchain technology to resolve data centralization problems, which is why the blockchain and the IOTA tangle and its operation will be included in our review of the literature on currently implemented solutions. Although BIM and GIS are both based on a structured and searchable database, BIM is mostly used for vertical infrastructures (e.g. buildings), whereas GIS is used for horizontal infrastructures (e.g. roadways).

According to Cocchia (2013), the digital city allows people to interact and share knowledge within a virtual digital space, but the idea of improving citizens' life is not explicitly laid out.

The smart city is a political initiative based on a sustainable development strategy and aims to improve the quality of life of citizens. This strategy matches the targets of the present study perfectly. The smart city considers the four city systems (population, government/municipal authorities, the territory and infrastructures), much like what is called for in the present study. However, it tackles the management of each system separately because each one is led by professional managers, who specialize in specific areas of expertise, and have multiple perceptions. Although the smart city banks on the use of technologies, it does, however, use different decision support systems, with each such system dedicated to a single management type. Of note though, is the fact that these technologies do not shape or aggregate the different managers' individual thought processes.

The human brain does not have the capacity to store a huge database or to query the different city systems. That is why managers use digital 3D models which highlight both convergent and divergent elements having to do with understanding the complexity of city management. Nevertheless, during the model design, most existing models are limited to visualization or a very specific analysis type.

A variety of management domains have emerged to handle city systems and challenges. Data, particularly respecting assets, water, transport, construction projects, environmental quality, wastes and human resources, is managed at the most basic level. All management domains resolve some of a city's problems, and this solution must comprise a holistic, global and transdisciplinary vision. The solution proposed for resolving the city's problems is based on interconnection of the different systems. Figure 1 illustrates how systems are managed and proposes a means for interconnecting them. The solution consists of managing all city systems in an integrated fashion with a view to their sustainable development and resilience.

The city's systems can be interconnected through digitization and the integration of new technologies into different management domains. Underpinning this is a searchable mega database of the entire city.
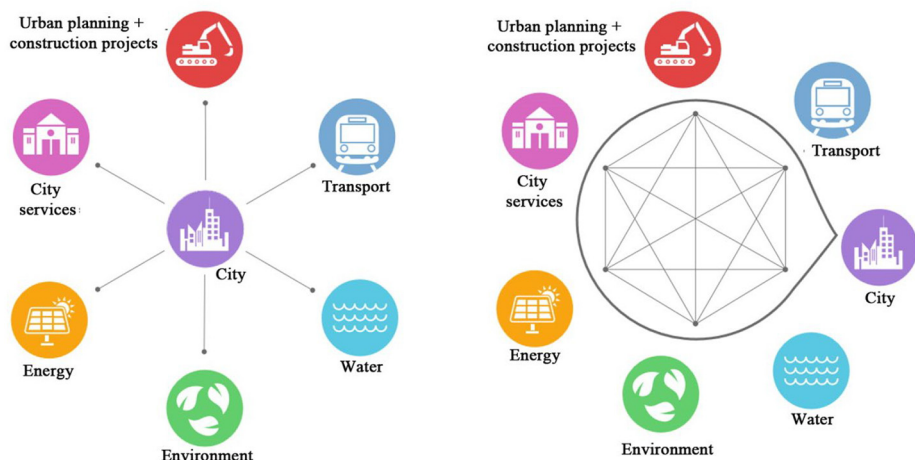
Figure 1.
Current systems
management and
proposal for
interconnection

The long-term objective of the present study is to develop a decision support system, based on a digital 3D city model. Given the scope of the project, the present paper aims at creating a digital 3D city model that is searchable, high performing and unique in its ability to interconnect with the city's systems to analyze data in real-time to extract relevant information for use in decision-making.

The paper presents a review of the literature, and is laid out as follows: Section 2 covers data management, the interconnection between the territory and infrastructures (combining BIM and GIS city information modeling (CIM)), and the interconnection between government/municipal authorities and the citizen (through the digital and the smart city). Section 3 presents an analysis of five digital 3D city models, as well as observations and analytics trends for the new model. Section 4 discusses the concepts underlying existing models, explains the benefit brought about by the proposed model and demonstrates its robustness. Section 5 concludes the paper with discussion and implications.

2. Key components of a 3D city model design
The digital 3D city model constitutes a large digital ecosystem comprised of multiple linked sources of data. Among the city's systems: the territory and infrastructures as mentioned at the beginning of the introduction. Each of these systems has already been separately considered as a database for managing the city. Processes already exist for modeling and querying the model (for example, BIM for infrastructures and GIS for the territory). To fuel this research and further study the databases that can be combined to build the model's mega database, it was necessary to search for information on the characteristics of the data and to identify (in existing sets) the key elements (BIM and GIS) and emerging elements (blockchain and CIM).

The digital 3D city model is based on digital data. It is used to present analyses and simulations, allowing better decision-making. These involve government/municipal authorities, which make up the third city system. It is in this context that the research focuses on the digital city because it is based on data digitization as per government

requirements. Moreover, the digital city is often confused with the smart city, both being technology-based. The smart city takes into account the quality of life of its citizens, as well as sustainable development principles. It is interested in the population, which is the fourth city system. Serious thought should thus be given to gaining a fuller understanding of both the digital city and the smart city concepts, and of what makes a city smart, as well as how technology can aid in city management.

2.1 Data management

The digital 3D city model will be realized, developed and queried in real-time based on data. To optimize the search time and ensure high-quality data collection, it is important to identify data requirements for modeling; consider the structure and media on which data will be stored; obtain proper data sources; and select a tool allowing speedy and precise collection. The amount of data available for the city is huge, and so we must know how to choose the appropriate data and plan how to manage and maintain it on an ongoing basis. Data security is also a critical issue that must be contemplated beforehand.

This section presents basic knowledge about data, namely, data collection tools, data analysis and presentation, storage, the importance of owning data, data security (Blockchain, IOTA project) and the smart contract. Because the 3D city model is based on data, this basic knowledge also underpins the model as well.

2.1.1 Data, information and knowledge. It is important to distinguish between the notions of data, information and knowledge. It is not easy to define them precisely (Floridi, 2013). For example, 360° images taken by a camera in a sewer line are data. A curve showing a deformation as it evolves over time is information. The fact that the sewer line deforms due to aging is knowledge. Figure 2 shows the path from data to knowledge.

According to Abiteboul (2012), the three notions can be summarized as follows:

- Data is the description of reality (an observation, a measure, etc.).
- Information is the fruit of the organization and structure of the data.
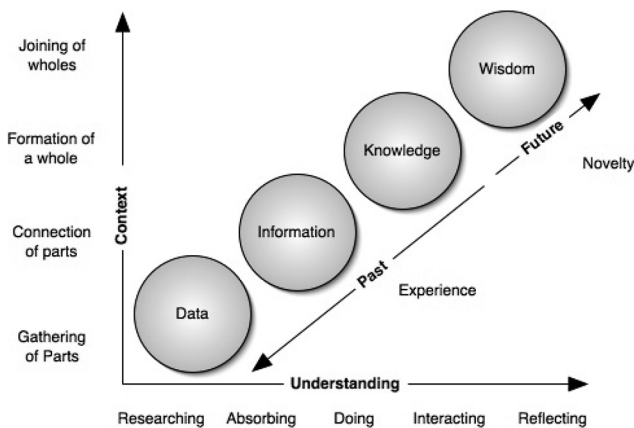- Knowledge is acquired based on how information is understood.

Source: From Clark (2004). Reproduced with the permission of Clark D

Data collected is raw data, and will, therefore, not allow "smart" management of the city if the information is not extracted from it. The digital 3D city model to be developed is a multiple linked sources of data and will perform better if it goes beyond its role of storing and structuring the city's data if it supports analysis and simulation by users and allows querying to support decision making.

2.1.2 Managing data for information dissemination. Information experts and scientists have studied complex computer systems extensively to collect data, extract and analyze information and transmit knowledge.

2.1.2.1 Data characteristics. Data are derived from multiple sources and form the basis for the management of assets, transport, energy, water, and for calculating the carbon footprint and meeting social and environmental objectives. Huge amounts of data on all of the city's systems must be considered to arrive at the best decisions. All data comes in a specific format (number, text, image), and category (vectorial, descriptive); data is also characterized by how it is collected (investigation and assessment methods, measurement strategies, existing data), evaluation parameters (priority, reliability/obsolescence, conversion efforts), costs (updates, outside mandates) and metadata (origin, date, author). All these characteristics together contribute to define the relevance of data, hence the need to identify data requirements for future designs of the 3D city model.

2.1.2.2 Data collection, analysis and presentation tools. Several tools allow data to be collected quickly and at high quality: cameras for televised inspection of pipes (360° high-definition camera, sound navigation ranging, etc.); new satellites, which allow the collection of reliable and accurate images (45 cm ground resolution, etc.); navigation and global positioning systems (GPS); virtual reality (VR) or augmented reality headsets allowing project site visits either before or during actual construction, etc. Figure 3 presents several data collection tools.

2.1.2.2 Storage. Advances in the understanding of the basics of algorithmics and its reasoning mechanics have now enabled the storage of large volumes of data. Furthermore, several storage media, particularly external hard and flash drives, are not only available but are easily acquired and allow storage of large volumes of data. Computer hardware is evolving at breakneck speed: "prices are dropping, access or transfer speeds are increasing, volumes are increasing" (Abiteboul, 2012).

To store data, there must be clarity in terms of its meaning, representation, organization and where is stored. For example, data may be stored in cloud infrastructures or in on-premise databases. Data storage in the future 3D city model to be developed is also something that must be thoroughly examined (Figure 3).

2.2 Importance of owning data
Data underpins all decisions. Some businesses use their clients' personal data to develop their marketing. According to the Boston Consulting Group (BCG) (2012), the personal data market will be worth €20bn in 2020. However, data management comprises certain limitations (e.g. ownership and sharing of the data), which necessitate certain decisions, and that is why owning data and being able to manage it is so important.

Information can now be obtained by querying database systems, which can be relational systems or Web-based information systems. The question that arises then is "Who holds information?".

In the case of Big Data, it is difficult to compile, store and analyze a large volume of data in a way that allows information to be disseminated accurately. This difficulty has led to fierce competition "between the FANGs in the USA (Facebook, Apple, Netflix, Google), the

Name	Characteristics	Photo of tool	Result
Aircraft	Overhead imagery - Ground resolution: ± 3cm - Clear day cover - High to medium acquisition cost		
Drone	Airborne imagery - Ground resolution: ± 3cm - Clear day cover - Highly wind-sensitive - Very low acquisition cost		
Total station/Robot	Station measurement - Ground pinpoint accuracy: ± 3cm - Operable at all times and everywhere - All climatic conditions - Need for processing and layout - Low acquisition cost		
LIDAR scanner	Color HDR imaging/3D point cloud model with polar coordinates - Ground pinpoint accuracy: ± 3cm - All climatic conditions - Medium to high acquisition cost Point scanning method		
References	(Blake, 2018), (Dionne, 2017), (Dnd, 2017), (Halama, 2017), (Leica Geosystems, 2018a, Reproduced with the permission of ©Leica Geosystems), (Leica Geosystems, 2018b, Reproduced with the permission of ©Leica Geosystems), (McGloin, 2015), (Rumble, 2018).		

Figure 3.
A few data collection tools

BAT in China (Baidu, Alibaba, Tencent) and the rich Fortune 1000 multinational companies" (Epstein, 2017).

It is in this framework that data centralization is raising alarms in certain quarters. Abiteboul (2012) questions how much search engines should be trusted in Europe, stating that "they yield considerable power by controlling information." Epstein (2017) directs attention to the FANGs, the BAT and the above-mentioned Fortune 1000 companies. They are the only entities with the means and capacity to obtain, store and analyze more and more data for transmission. Neuer (2018) shares this apprehension: "those who hold data have power." Given this framework, certain other questions must be considered with respect to

security (manipulated or stolen data), the possibility of faulty algorithms, the increasing quantities of data, ownership rights and personal rights. These factors are at the root of the ongoing debates on personal data protection, as well as legislative bills being brought in to deal with the issue. The Facebook-Cambridge Analytica scandal comes to mind in this regard, as well as the entry into force of the European Union's General Data Protection Regulation. In some respects, owning and managing data allows control over traces they leave in the digital environment. Serious thought must be given to securing ownership and management of the future 3D city model data.

2.3 Blockchain, IOTA project and smart contract

A few solutions have already been implemented to tackle the problem of data centrality. One example is the blockchain. It first emerged in 2008 with the bitcoin digital currency and remained almost unknown until 2015 (Kinnaird, Geipel, & MBE, 2017). Today, the blockchain concept has been extended to other fields (Blockchain France, 2020). It is a solution aimed at decentralizing and securing data transparently; a "decentralized, distributed and public digital ledger that is used to record transactions across many computers so that the record cannot be altered retroactively without the alteration of all subsequent blocks and the consensus of the network" (retrieved from https://en.wikipedia.org/wiki/Blockchain). The blockchain is uniquely different from other databases in that it involves no "central authority. There is no intermediary", such as a bank, to transfer money, or a lawyer, to confirm the terms of a contract (Koutsogiannis & Berntsen, 2017). Figure 4 illustrates the blockchain principle.

A second example is the IOTA project, which proposes a large-scale interaction between smart devices. Figure 5 presents the IOTA tangle and its operation, which is comparable to blockchain systems in terms of decentralization and security.

According to Koutsogiannis and Berntsen (2017), the blockchain allows overall greater transparency and accountability and better project control, while improving workflow and keeping minimizing conflicts and risks. Thanks to the blockchain, the data source is thus known, and the ownership is defined. The blockchain could also enable a faster and more data-driven decision-making process, as is already the case when using construction software. However, 95 per cent of construction industry data are not computerized (Koutsogiannis, 2017). The smart contract example illustrates the blockchain's capacity to "add more transparency to every type of agreement and transaction in a construction project" (Koutsogiannis & Berntsen, 2017). A smart contract is a digital protocol based on a controlled process and on the blockchain to enable open transactions without any intermediaries (e.g. lawyers) involved.

Data structure and information flow in the 3D city model to be developed may be based on the blockchain and/or on the IOTA principles. The process is controlled, the data source is known, and the ownership is properly identified.

Source: From Blockchain France (s-date), reproduced with the permission of Blockchain France

Figure 4.
Representation of the blockchain principle

3. From data digitization to the smart city based on the digital city

3.1 Interconnecting the territory to infrastructures (two city systems)

The literature review identified several possible solutions to model the city by interconnecting two of its systems, namely, the territory and infrastructures: BIM/SIG combination, the use of BIM for infrastructures, CIM, as well as BIM and the blockchain.

3.1.1 Building information modeling, geographic information system and CIM. Horizontal infrastructure management is based on data collected using geomatics, that is, the automatic processing of geographical information. Currently, the digital city model is an urban digital information model based on geospatial infrastructure data obtained through GIS technology.

Management problems related to vertical construction cannot be resolved using two-dimensional data appearing in drawings. That is how the BIM has been adopted in some countries in accordance with government requirements.

A combination of GIS and BIM can resolve management problems for all types of infrastructures (horizontal and vertical). When used for infrastructure management, BIM is called CIM (McGraw-Hill, 2012) or "BIM for civil engineering works."

Hutsel and Bush (2016) confirm BIM, GIS and CIM are currently being combined ongoing. Their integration and interoperability are enabled by the implementation of standards and best practices. That is how a language that can be included in all contracts to create a geospatial link develops. To manage a large digital ecosystem comprised of multiple linked sources of data, known as the 3D city model, the real-time application of various data sources, as well as the availability of these data for the entire duration of the project, must be guaranteed. Moreover, a geospatial benchmark must be created for the entire geospatial life cycle.

3.1.2 Building information modeling for infrastructures. Government/municipal authorities have stringent requirements regarding efficiency standards and deadline observance. It is estimated that by 2025, large-scale digitization of the built-up urban area will produce cost savings ranging from 13 to 21 per cent during the design and construction phases, and from 10 to 17 per cent during the operating phase of the structure (Boston Consulting Group, 2016). Industry 4.0 is the "fourth industrial revolution driven by the integration of digital technologies in the core of industrial processes" (Mckinsey Global Industry, 2017).

BIM is an integral part of this revolution. According to Teo Ai Lin (2017), it shortens completion times, improves quality, productivity, performance and competitiveness. It
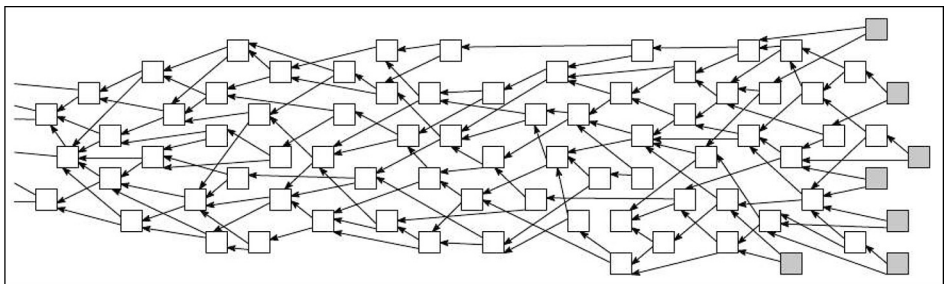

Figure 5.
Illustration of the
IOTA principle

Source: Reproduced from Wikimedia Commons (2017)

provides a source of federated and reusable information through 3D modeling. BIM can provide several benefits for construction project management, and thus foster improvements in decision-making. Gould (2010) proposes that BIM should be directed mainly toward management by combining the social and technological aspects of construction projects. It enables real-time testing, analysis and simulation to provide greater energy efficiencies and better cost management, even before construction begins. It also leads to reductions in waste and accommodative developments (Azhar et al., 2008; Bentley, 2018; BIMhub, 2018). It is a process that is operational for the entire life cycle of the asset (Howard & Björk, 2008; Rezgui, Beach, & Rana, 2013).

BIM is mostly used to manage vertical construction. Some authors believe that BIM will find new applications for which it was not originally designed, including in areas such as infrastructural projects (Bradley, Li, Lark, & Dunn, 2016). This has been observed as BIM has begun to be integrated into infrastructure projects (other than buildings), including in the construction of the Doha metro (2022), the Atlantic Bridge in Colon, Panama (2018) and the Crossrail regional express railway (RER) in the UK (August 2018).

BIM can bring provide benefits to the different city systems, including construction project and asset management. We now examine a few applications.

3.1.2.1 Roadway management City traffic can be managed using an urban traffic information model (BIM, jointly with GIS) to help manage traffic. Having a 3D model of a road presents several advantages, including, for example, simulation of drainage at the design stage. This model also helps determine if speed limits should be adjusted to allow smooth traffic flow and if congestion levels can be monitored and analyzed. In addition, through warning signals, road users can be alerted of dangers on the road and traffic jams.

Highways England adopted the modeling-based Smart Motorways program not only to solve the congestion problem but also to improve safety (SmartMarket Report, 2017). This program aims at facilitating asset data management. Designers use virtual reality VR to keep contractors constantly informed and even to steer machines on building sites. They also anticipate using robotics in digging trenches.

3.1.2.2 Water management Cities contain water bodies (rivers, seas, etc.), and the urban water cycle is becoming increasingly vulnerable to climate change. As well, they have wastewater management and potable water supply systems.

The term *wastewater* pertains to sanitation sewage from households as well as industrial and institutional waste and surface runoff in urban areas. Water is indispensable for life, and its pollution has enormous consequences on citizen health. Runoff regimes can reach or even exceed 100 times the dry regime, and the surplus from this mixture is discharged untreated into the receiving environment (stream, river, lake, sea, etc.). It is thus crucial to be able to use modeling in designing and assessing drainage infrastructure behavior, both in new developments and in the rehabilitation of existing urban drainage infrastructures.

3.1.3 Building information modeling and blockchain. The use of the BIM models means that data is shared between several stakeholders (architects, engineers, etc.) on the cloud through a *Common Data Environment*. The model is thus vulnerable to piracy and manipulation of data, which are centralized.

According to the Arup Report (2017), the solution is the use of the blockchain during the design and construction phases. The blockchain records every action in the model and does not allow any changes or deletions, which increases trust among stakeholders. With this data transparency established, each stakeholder can demonstrate their intellectual honesty, whereas digital components can be shared without changes being permitted; an example is the case of families in Revit. After the project is delivered, the blockchain offers the possibility of connecting the digital to the physical. Adding a chip to any device connected

to the internet would enable the transmission of real data, thus enabling monitoring throughout the entire project life cycle. The chip would also help identify all the characteristics of the device, including the location of materials to be recycled (circular economy).

3.1.4 Building information modeling adoption policy and competitiveness. With expected future competition in the global construction market, countries in which BIM has not yet been adopted will risk losing out on market opportunities offered by BIM in major construction contracts, both domestically and internationally. The desire to push innovation and lead the industry is the driving force behind the BIM policies of the UK and Singapore. One of the goals of the global construction strategy in the UK is to ensure that its construction sector is competitive, efficient, productive and capable of exporting design and engineering services to other parts of the world. BIM is a part and parcel of the required skills (Eadie, Odeyinka, Browne, McKeown, & Yohanis, 2014).

Singapore, one of the global pioneers in BIM, has often imported design and construction services to meet its growing demand and benefit from the most effective methods and tools available. According to Teo Ai Lin (2017), economic growth is Singapore's strategic priority. Its BIM mandate and road map aim to reverse the importation trend and allow Singapore-based firms to become competitive against their international counterparts, which should support job creation and income for the local industry (Bosquet, 2017).

It is, therefore, crucial that government/municipal authorities require the adoption of BIM within their respective territories. The future searchable 3D city model will thus leverage the strengths of existing BIM infrastructure models. BIM/GIS interoperability will enable managing a single data source, i.e. the 3D city model.

3.2 Interconnecting government/municipal authorities with citizens (two city systems)
The end-goal of the present research is to improve managers' effectiveness, to enable them to make better-informed decisions for infrastructure sustainable development and to provide the best possible services to citizens both today and in the future. The desired outcome is a healthy, sustainable and resilient city through the use of technology. This vision overlaps with a combination of two visions, namely, that of the digital city and that of the smart city. Will the searchable 3D city model perform better and be developed more easily because the city will be digital and/or smart? It is thus crucial to gain a deep understanding of these two existing concepts to be able to propose better solutions for the future.

Authors differ not only in how they call the smart city (e.g. *cybercity*, digital city, green city, etc.) but also in how they conceptualize it, depending on the context. There is added confusion between a digital city and a smart city. This section defines the digital city and the smart city and lays out their differences and similarities; it also highlights elements that interconnect some city systems within the two concepts.

3.2.1 Digital city. This paper proposes three definitions of the digital city, and although the three are formulated differently, they are identical in meaning. To Qi and Shaofu (2001), the digital city is:

> [...] an adaptable system based on a computer network and urban information resources, all constituting a virtual digital space for the city. It creates an information service marketplace and an information resource deployment center.

Schiewe et al. (2008) and Dykes (2010) define the digital city as a functional approach consisting of four actions:

• supporting urban data in digital format;
• providing a communication infrastructure (physical or virtual);

- analyzing and processing data to obtain relevant information; and
- using a virtual environment for decision-making planning and analysis.

The most popular definition is the one proposed by Ishida, in his study entitled *Kyoto Digital City*, which targets CO_2 emissions reduction. The author defines the digital city as "an arena in which people can interact and share knowledge, experiences, and mutual interests" (Sorrentino & Simonetta, 2013).

These definitions include several elements and subjects of the present research. Decision-making in the city, which is based on data digitization and analysis, is included in the definitions. The limitation of CO_2 emissions is a component of the sustainable development research vision. Ishida explains that the digital city is a virtual collaborative space between people (Sorrentino & Simonetta, 2013). This definition fits right in with the 3D model that this research wishes to develop.

3.2.2 Smart city. Several definitions have been proposed for the smart city, but none is universally recognized (Cocchia, 2013). These definitions are not mutually contradictory, and all have common characteristics (Dameri, 2013). To enable a comprehensive and complete understanding of the term, this paper proposes three definitions.

Northstream (2010) presents the smart city as one in which public services connect "seamlessly" using ubiquitous technologies, to significantly enhance urban life quality. To Hall (2000), a smart city is "a city that monitors and integrates the conditions of all of its critical infrastructures, including roads, bridges, tunnels, railways, subways, airports, seaports, communications, water, power, and buildings; optimizes its resources; plans its preventive maintenance operations, and monitors security components, while maximizing services to its citizens." SETIS (Strategic Energy Technologies Information System) (2012) considers a smart city as one that "can combine technologies as diverse as water recycling, advanced power grids and mobile communications to reduce the environmental impact and offer a better quality of life to its citizens".

The first point that pops out in these definitions is that the smart city is interested in the quality of life of its citizens. This subject is not covered in the other processes or concepts presented in this paper. Resource optimization and the principle of sustainable development are also included. Technology use in the different management types, as is required in the present research, is encouraged.

3.2.3 Differences and similarities between the digital city and the smart city. According to Cocchia (2013), the main differences between the digital city and the smart city lie in their contents, nature and relations. The digital city is an emerging "free" trend arising from the use of digital services provided by the government, whereas the smart city is a policy trend aimed at improving the quality of the urban environment. In other words, the digital and smart cities differ in both their objectives and strategies, as well as in their implementations. The definition of the digital city is based on the idea of collecting data using information and communication technologies (ICTs). Citizens play a less proactive role and the idea of improving their quality of life is not explicit (Cocchia, 2013). Conversely, smart cities are assessed through physical indicators such as CO_2 and greenhouse gas emissions, waste tonnage and the number of megawatts of energy from renewable sources (Al-Hader, & Rodzi, 2009). At its core, therefore, the smart city consists of the sustainable development strategy adopted and of the use of its own natural resources to improve the present and future quality of life of citizens.

Despite these differences, the concept of the digital city overlaps with that of the smart city (Yuan et al., 2012; Lombardi et al., 2012), as both use technology, more specifically, ICTs,

to improve the city's economic development. For example, for IBM, the city is run based on three systems:

(1) service planning and management;
(2) infrastructures services; and
(3) human services.

Each of these constitutes a separate system since the city is a system of systems (Söderström et al., 2014). It is against this backdrop that IBM started supplying governments with smart communications, energy and public service, health care, insurance, retail, transport and other solutions (Cocchia, 2013). The smart city designed by IBM is, therefore, also digital.

The objectives of the smart city overlap with those of the present research, with the interconnection between government/municipal authorities, citizens and infrastructures is strongly represented. The vision for the present research is identical to that of a smart city. The 3D model to be developed for the city is indeed the 3D model of a smart city.

4. Creation of a new 3D city model

The last section covers the key elements of the design of the 3D city model, i.e. the different existing processes and solutions. Now, this paper will study 3D models of existing cities and propose a new model based on a review of the literature.

Data visualization and storage are characteristics of information-rich 3D city models that can be widely implemented in urban planning, decision-making and urban space management (Koeninger & Bartel, 1998; Lee & Kwan, 2005; Ross et al., 2009; Qing et al., 2009). An ever-growing number of cities are being modeled in 3D (Mao et al., 2014). Several cities, Abu Dhabi, for example, have used 3D models and several companies (for example, Google) have also integrated 3D city models in their services. The models are designed in many different ways and used to achieve different objectives, including urban visualization and planning, as well as noise management, water management, etc.

4.1 Description of five 3D city models

Five 3D city models were selected for analysis. These models were chosen based on various criteria, including different countries and dates, different owners and objectives underlying their creation and different techniques and technologies used.

3D model of the city of Hong Kong: The city of Hong Kong faces major road traffic problems. Its vehicle density for 2009 stood at approximately 283/km (Information Services Department, 2009). Home to many 40-60 floor residential buildings, it is the city with the highest population density in the world. Building facades are exposed to noise, and to attenuate this noise, the city used GIS to design a noise contour map for gathering noise-related information and quantifying the noise scale, as well as assessing noise attenuation measures. The information presented in a 2D map was limited as it did not show the vertical variation of noise levels, which is why the city then proceeded to adopt an interactive 3D noise visualization model. The model was able to send noise results to users (professionals and the public) to allow a fuller understanding and improve the situation.

4.1.1 3D model of 11 cities in France. A project to acquire a realistic digital 3D model was kicked off in 2004 and lasted more than eight years. 3D models are loaded into a small radius, and to ensure a smooth operation, buildings far from the camera are shielded. This model is different from Google Earth models in its greater precision. The level of detail of the model is available as LOD1 and LOD2. According to the Yellow Pages (2007), the model has

been used in a variety of simulations. Following this experiment, the city decided to launch another more precise 3D model.

4.1.2 3D model of Chennai in India. In 2008, the city of Chennai was developing at a pace that far exceeded any temporal-spatial planning it had undertaken. Urban planners were under constant pressure. To meet the challenges they were facing, they used different modeling tools, including computer-assisted design and SIG. They created a model to help improve their decision-making. The model was generated from ArcMap to ArcScene, both ESRI tools. 3D modeling aimed to measure the impact of urbanization on existing infrastructures, specifically the capacity of sewer systems to handle greater wastewater volumes, which should allow better planning.

This experiment concluded that "analyses must be holistic" and all physical and social infrastructure parameters must be integrated alongside zoning regulations (Ahmed & Sekar, 2015).

4.1.3 3D model of London in England. A 3D model of a $25\,km^2$ surface area of Central London was realized. The base 3D model was captured manually using stereophotogrammetry. The source photograph and associated data were obtained from the last high definition 12.5 GSD images collected in August 2016. The modeling of vertical infrastructures was accurate to 90 cm in all axes. The terrain in the base 3D model was not flat. It was captured manually using the same photogrammetry method as in the building and was accurate to 20 cm in all axes at the edge. The model was easy to use and update. The files were structured as 500 x 500 m $(0.25\,km^2)$ OS mosaics, which made it easy to modify or replace them by zone without having to modify the entire model. The rationale for 3 D modeling was commercial. AccuCities, a private company, was the supplier of the data, which it models and sells to clients, who include planners, developers and architects.

4.1.4 3D model of Abu Dhabi in UAE. In 2018, the Indian company, Rolta, based in Mumbai, and which has worked in Dubai and Oman, won the contract to develop the 3D model of the city of Abu Dhabi. It was a high-precision model, with photorealistic building facades. Unfortunately, the present research cannot provide additional details on the techniques and technologies used. Modeling was aimed mainly at sharing the internal database with other relevant government/municipal bodies. The model allowed the management of services and assisted in rapid urban planning. It facilitated emergency responses and improved public security.

Table I summarizes the different approaches used to design the 3D models of the chosen cities. Only available data are specified in detail.

4.2 Analyses, observations and proposals

Several observations could be drawn from the analysis of five 3D city models. 3D city modeling is not a new idea. In 2002, Hong Kong used it to help its managers in their decision-making. During this period, and in fact, even before then, managers had understood the limitations of managing a system based on a 2D database. They had also fully understood that 3D modeling could be used for much more than just visualization.

The idea of modeling the city of London by zone really is of immense help when it comes to allowing support for a greater data volume. It facilitates modifying and updating the model. Nevertheless, this idea must be extended if the model is used to analyze and simulate models outside the zone limits. AccuCities sells the city of London 3D model, and to meet their specific needs, clients can add to and improve on it. The ability to adapt the model to meet specific needs is also a very good idea. However, the notion of collecting data, and then modeling and selling the model, leads to questions regarding data ownership, which we

Model	3D model of Hong Kong in China	3D model of 11 cities in France	3D model of Chennai in India	3D model of London in England	3D model of Abu Dhabi in UAE
Modeled area	2,700 km²	11 cities	60 m²	25 km²	Over 5,866 km²
Start of modeling	2002	2004	2008	2016	2018 (ongoing)
Designed by	City of Hong Kong (Public)	Yellow Pages (Private)	Chennai Metropolitan Development Authority (Public)	AccuCities (Private)	City of Abu Dhabi (Public)
Target objectives / strategies	Reduce City of Hong Kong road traffic noise. Roads are situated close to skyscrapers and this affects the vertical variation in noise levels. This makes existing 2D noise maps imprecise	- Visualize. - Offer a 3D volumetric representation and view of buildings and vegetation	- Visualize and improve urban planning - Collect all necessary data for decision-making; for volumetric and other environmental analyses. For example, the model has been used to verify whether the densification of the urban center matches the existing infrastructure capacity or if the latter has to be developed	Create and sell a model to paying clients, including planners, developers and architects. AccuCities develops applications for its clients, who then develop others (e.g. GVA)	Manage services and enable rapid urban city development Facilitate emergency responses and improve public security Share the internal database with the relevant government/ municipal bodies
Technologies used	Integration of acoustic modeling, GIS and other tools to obtain a representation of the real acoustic environment 2D noise mapping and 3D presentation tools	CityGML and standard and low-resolution photographs. Facade handling through texture mapping of low-resolution photographs Representations comparable to those of Google Earth/Google Maps	With the help of field verifications, extrusion to ArcScene of a map redrawn on ArcGIS Modeling carried out from 2D basic creation and Google imaging used to determine the number of floors Addition of all spatial and non-spatial data as attributes	Solid AutoCad . DWG, SketchUp . SKP and .FBX to facilitate editing. Manual capture from 2016 aerial survey. 90 cm precision 3D printing-ready Unreal Engine Version 4 included	Photo-realistic processing of external building surfaces before proceeding to internal building surfaces Several landmarks modeled at higher precision
References	Law, Lee, Lui, Yeung, and Lam, (2011)	Yellow Pages, (2007)	Ahmed and Sekar, (2015)	AccuCities, (2018) GVA, (2018)	Zaman, (2018) Abu Dhabi City Municipality, (2018)

Table I.
Different approaches to designing 3D city models

covered earlier in section 2.1.3. Some private companies appropriate the city's data, which they then go on to sell back to the city itself.

There are several 3D models of cities available, but in each case, modeling is done differently, depending on the strategy and objectives of the model owner. Sometimes, private companies wishing to sell the model to planners, developers, etc. (models of London and French cities), initiate the modeling for commercial reasons. Sometimes, it is the local government that initiates the model, which it considers a decision-making tool. It is, therefore, clear that no global vision exists, which makes it difficult to perceive the full potential of 3D city models.

While a model may carry out analyses with a specific objective, none of the 3D city models identified during the research was searchable over several sectors. Existing models do not produce a dashboard to help managers steer the city based on real-time performance indicators and a global vision.

The structure of the 3D city model and technical choices depend on limited design objectives, and this structure then limits the model's potential. Because the techniques used are limited to visualization and a few analyses, these models lack the capacity to interconnect all urban systems and perform several analyses (e.g. carbon emission levels, disaster management, etc.).

4.3 Towards a 3D smart city model

3D modeling, analysis and simulation tools have become more sophisticated, and the latest models are extremely precise. This proves section 2.1.2, which explains the availability of tools used for large-scale modeling.

The solution proposed in the present study to tackle urban management problems and to predict the impact of decisions before they are made is a new type of 3D city model. It is a parametric digital 3D model (or virtual 3D model) of all of the city's infrastructures. It provides virtual, augmented, and mixed reality visualization and presentation. It also helps ensure that standards are observed and provides coordination and simulation as well as management of deadlines and costs for the entire life cycle of assets.

4.3.1 Benefits and peculiarities of the proposed model. The proposed model aims to assist in the integrated management of all city systems. It covers all the functions of the models cited in section 3.1.1 (visualization, improvement of urban planning, noise analysis, etc.), and allows the following objectives to be met: asset management; transport management; construction project management; quality and environmental management; water management; waste management and recycling, etc.

4.3.1.1 Model that interconnects all systems. No system operates in isolation. The proposed model requires that systems be interconnected. This paper presents a review of the literature on different existing solutions.

City management involves the management of infrastructures, that is, the management of all data used in decision-making, including management of civil engineering and environmental data, topographical data, geotechnical and geological data, asset management, management of current or planned work, space management, risk management, etc. Consequently, the 3D city model must be analyzed holistically and integrate all physical systems, social parameters, regulations, etc.

4.3.1.2 High analytical capacity model. The robustness of the proposed 3D model lies in its capacity to analyze different trends considered in decision-making. Table II summarizes anticipated trends that will need to be developed depending on the particular context.

4.3.2 Attenuation factors of the model. With modern technology, we can predict that the 3D city model design proposed in the present study will be successful. Today, both the

Management type	Analytics trends (a few examples)
Data management	Collect, store, analyze and disseminate data
	Control data efficiency and effectiveness
Asset management	Analyze the required service level (e.g. street lighting)
Managing spaces and new construction projects	Integrate and verify compliance with town planning regulations (e.g. zoning)
	Analyze potential for solar
	Analyze noise level
	Analyze the energy efficiency of built structures
Urban traffic management	Optimize the movement of persons and goods from one place to another
	Analyze safety and accessibility
	Simulate the environmental impact of transportation modes
	Analyze the maintenance of urban traffic and road congestion
	Manage airport solutions
	Assist in urban road design and management
Water management	Monitor rainwater runoff volume and time pattern
	Detect and analyze the probability and frequency of backups and floods
	Anticipate potential water pollution, and therefore, protect water body quality
	Study the optimal distribution of water and its long-term availability
	Evaluate the functionality of drains
Management of environment quality	Energy:
	Study the possibility of optimizing energy consumption
	Analyze the best way to distribute gas
	Analyze urban heating/cooling
	Carbon:
	Estimate greenhouse gas emission volumes
	Pollution:
	Process environmental parameters when designing construction projects
	Assist in waste management and recycling: Circular economy
	Comfort:
	Manage air temperature and humidity to ensure appropriate indoor climate, etc.
Management of risks and public security	Provide smart public services (for example, real-time video monitoring)

Table II.
Towards a 3D smart city model

internet and the Internet of Things are accessible to all. Artificial intelligence is set to conquer the whole planet. Smart systems are more interconnected than ever before, making it easy to create a smart city. An unlimited amount of data can easily be stored in a Big Data warehouse or the cloud. Tools, software and platforms are available and have become competitive. Geomatics has become indispensable in several cities, and its new tools are more powerful.

5. Discussion and implications

Several problems are encountered when managing cities and are mainly attributable to a single source, namely, data exchange and management, which underlie all decisions taken. Each management type resolves a part of the city's problems but does not take into account the interconnection between systems. The solution proposed in the present research consists of integrated management of all city systems with a view to ensuring sustainable development and resilience. It is in this context that this research proposes a new digital parametric 3D model of all the city's infrastructures. Its first objective is to connect all of the city's systems (Figure 1).

In Section 2, the literature review demonstrates the importance of data and of owning and managing them. The model will perform better because it goes beyond its role of merely

storing and structuring the city's data, it succeeds in analyzing and simulating data and extracts information needed for decision-making.

This literature review identifies existing trends, concepts and processes that can be used by managers to optimize their decision processes (BIM, CIM, GIS, Digital city, Smart city, Blockchain). The new model can thus harness the potential provided by all these success factors: it must employ data security and transparency concepts such as the IOTA project principle, and the blockchain is also a must. The model combines BIM, GIS and CIM. BIM is used not only for buildings but also for urban infrastructures (e.g. bridges, roads, etc.). The study of the concepts of the digital city and the smart city concluded that the vision for the present research is identical to that of a smart city. The objectives of the smart city overlap with those of the present research. The 3D model to be developed for the city is indeed the 3D model of a smart city.

There are several 3D city models in existence, all of different types. The literature review in Section 3 analyzes five 3D city models. The design of these models (structure, techniques used, etc.) depends on the model owner, their strategy, and objectives. In other words, the strategy underpinning the design lacks an overall vision of the city's problems, and thus prevents it from exploiting the 3D city model to its full potential. None of the digital 3D city models identified in this research can be queried for several sectors. The existing models are not based on indicators that come from several management areas because they are not based on a global vision of integrated management.

This section, therefore, proposes the analytics trends for the new searchable 3D city model. The model has a high analytical capacity and is not only limited to visualization, town planning improvement or noise analysis but also includes all parameters that allow the management of assets, urban mobility and transport, construction projects, environmental quality, water, etc. It is capable of predicting the impact of decisions taken by the city's managers.

The new model enables data fluidity, collects data in real-time and analyzes and simulates them while ensuring coordination between different city system datasets. A dashboard that synthesizes and presents information is integrated into the model. The shape of the dashboard is yet to be developed, but the option chosen here is a humanoid form that discusses and debates city management strategies and presents results.

This model design requires the collaboration of several stakeholders: the government, industry, professional associations, researchers, etc. Success in designing such a 3D model cannot come without a public mandate to accompany and support the city's digital transition. The proposed model is in its conceptual phase and must factor in specific contexts during its implementation. The paper goes on to reflect at length on the techniques and technologies to be used as well as the level of development and detail needed and allows a reflection on the multi-platform workflow.

Admittedly, the model may have some shortcomings, such as risks related to information security, its inability to handle emergencies or the risk of political non-acceptance, among others. However, today's shortcomings will, in fact, be good points to ponder during the design phase.

All that is now left is to trust human intelligence and use the proposed project to ensure performance, value and efficiency.

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