Geographical Information Management and Applications

The Role of Geospatial Technologies in Building Smarter Cities

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Summary

This thesis reviews the smart city concept in relation to geospatial information and technologies. It aims to do so by defining the ideal smart city information system and comparing this with a prototype geospatial information model. Also, an overview is given of geospatial applications in smart city development. As cities are spatial entities, geography and geospatial technologies can play a major role in enabling the smart city concept (Percivall et al., 2015). Geographic Information Systems (GIS), being ICT technology, can therefore serve as centralized information systems which integrate all aspects of processes in cities that wish to be 'smart'.

Smart city approaches, technologies and trends, standards, data, architecture and applications are described in Chapter 2. To come to a definition of the ideal smart city information system and what its requirements are it is proposed that it should be able to measure indicators of smartness, as is proposed in multiple approaches. This requires a stable information architecture which is interoperable, functional, extensible, secure, and transferable and which should be able to incorporate different technologies using (open) smart city standards. If this is the case it can serve as an ideal basis for the development of specific applications. Open standards are needed for interoperability between systems, but also for efficiency, application innovations and cost effectiveness. Smart cities require a framework of trusted/authoritative data; for example, core reference data in 2D and 3D (i.e. topography), identifiers and addressing, smart infrastructure (BIM, smart grid), and sensor feeds (Percivall, 2015). These are types of spatial information that are crucial for building smarter cities. Such a framework, based on spatial information, needs a data integration platform, which is provided, in part, by the OGC City Geography Markup Language (CityGML).

Chapter 3 describes spatial information, what it is, how it viewed upon from a smart city perspective, what GISs can do, what an SDI is, which (geo-)standards there are (in particular CityGML), what techniques exist and what applications can be built. From this it is argued that 3D geo-information and data is particularly useful for buildings smarter cities. This is then being tested with the development and construction of a prototype 3D Virtual District Model of a future scenario in a case study for the Smart Sustainable Districts project in Utrecht. This 3D city model can serve as part of a Smart District Data Infrastructure and be used as 'backbone' for further smart city development. The method or design scheme for this can be copied to other districts or areas.

The proposed prototype is a showcase of how the first steps towards an integrated CityGML based 3D city model can be taken. The potential use of 3D city models is great and there is a lot to win in building smarter cities. Geospatial information and technologies must become a greater role in this.

Contents

1. Introduction

As of 2016, an estimated 54.5% of the world's population is living in urban settlements and this number is increasing (UN, 2016). This provides great challenges for urban planners and alike because many concerns must be considered when trying to achieve or maintain a high quality of life in cities. Challenges that are facing modern cities include becoming resilient towards climate change, adapting to emerging economic markets, global competition, migration, industrial decline, ageing population, persistent inequality, dealing with citizens, pace of service innovation, ageing infrastructure, lack of overall control, money (BSI, 2015).

Although many benefits come along with the trend of population concentrating in large and dense cities, negative aspects can also be measured. Noise pollution, air quality, energy usage and production, traffic flows, to name a few, are among these aspects.

At the same time, with the rapid development in ICT technology and services in the past decades, cities therefore are looking for new approaches to cope with the challenges that arise. One of these new approaches is broadly called 'Smart Cities' (Harrison & Donelly, 2011). The concept of a 'Smart City' involves the systematic integration of ICT and technologies in cities, presumably leading to better services and a more sustainable living environment with citizens in a centric role. As Yin et al. (2015) define it: "*A smart city is a system integration of technological infrastructure that relies on advanced data processing with the goals of making city governance more efficient, citizens happier, businesses more prosperous and the environment more sustainable*. "

Worldwide, many cities nowadays have the intention of becoming a smart city, as can be seen by the number of cities (700+) that participated in the 2018 Smart City Expo World held in Barcelona (Fira Barcelona, 2018), for example. However, the process of becoming one is not clearly defined and is not a one-size-fits-all solution. Even the term 'smart city' can be interpreted in different ways, as can be read in chapter 2. In general, implementing the smart city concept in whatever way, is said to open up many possibilities, improving the quality of urban life and providing a living experience that is dominated by technological solutions for reducing the negative aspects of city life and promoting new ways of city governance. Smart cities are coined to be the future of urban habitation and governments worldwide are preparing the roadmap for developing existing cities (Chaturvedi, 2019).

As cities are spatial entities, geography in general and geospatial technologies in particular, play a major role in enabling the smart city concept (Percivall et al., 2015). Geospatial technologies provide the foundation of smart cities and its applications. It provides location which allows to pinpoint exactly where solutions have to be applied. Geospatial technology provides a necessary framework for collecting data and transforming observation in these collections to facilitate software-based solutions around smart infrastructure. For instance, Geographic Information Systems (GIS), being ICT technology, can serve as centralized information systems which integrate all aspects (positive and negative) of processes in cities that wish to be 'smart'.

Also, planning future scenarios will become reality as integrated smart city platforms enable cities and citizens to use information systems that can integrate information from heterogeneous sources such as GIS, BIM, sensor networks, Internet of Things (IoT), etc. This will lead to better citizen services, better disaster and emergency management, and better energy and utilities management, to name a few of the possible applications smart cities and geospatial technology provide.

1.1. Context

This thesis reviews the smart city concept in relation to geospatial technologies such as GISs. It aims to do so by defining the ideal smart city information system and its requirements and comparing this with a prototype geospatial information model. Also, an overview is given of (geospatial) applications in smart city development.

This thesis results from the work done for the Smart Sustainable Districts (SSD) project in Utrecht, The Netherlands. This project has shown that there is a need for a better understanding of the relationship between smart city concepts and geospatial technologies. As such, the project will serve as a case study and the model that has been developed will serve as a prototype. For this prototype, consisting of a 3D city/district model which is part of a Smart Sustainable District Infrastructure (SDDI), the first steps towards a useful model have been made. The outcome is then evaluated.

1.2. Problem statement

The wish of making a city 'smart' and sustainable leads to an urgent need for the development of a stable information architecture which is interoperable, functional, extensible, secure, and transferable (Moshrefzadeh et al., 2017). But as there are many cities expressing this goal, as well as many other organizations such as companies, there seems to be many roads presumably leading to Rome. Since the term smart city has been introduced there has been a proliferation of smart city definitions, technologies, standards, and applications. But what is a smart city exactly? What are the most important characteristics? What are its requirements? And how to build one? As can be read later on, there is no absolute, straightforward definition of a smart city. But some key characteristics and requirements can be identified.

Information is vital to the functions of cities and the role cities play in society. One of the most used and most important information types is spatial information. To use this spatial information in combination with other types of information, geospatial components combined with other and new technologies may play an important role in developing smart cities. Interactive web maps, as a specific example of these combined technologies, can visualize, organize and interpret relevant data about mobility (traffic, construction sites, optimal routes, etc.), infrastructure (signs, road damage, etc.), and public health (location of hospitals, spreading of diseases), among many other things. These interactive maps are merely an example of an application that different stakeholders in smart city development can use to collaborate, discuss, interact, and make decisions.

In this study it is argued that when building smart cities, using geospatial technologies is an important, if not the first, step in making use of the data that is already available in cities. The problem that seems to be reoccurring is that smart city developers underestimate the role of geospatial technologies and spatial information in building smart cities or have insufficient knowledge of the strength and possibilities of GISs. Data are usually locked away in spreadsheets, pdf's and other documents and are hardly accessible. Making this data available through the use of geospatial technologies can help in improving accessibility and in improving general support.

1.3. Research objectives

This thesis aims to point out the overlap and difference between smart city concepts and geospatial concepts. There is insufficient knowledge and literature available that describe geospatial applications in smart city development and how geospatial information models compare with smart city information systems. To do so, a number of objectives has been defined:

- Understanding the relation between smart city concepts and geospatial concepts
- Define the ideal smart city information system and its requirements
- Give an overview of geospatial information systems and applications
- Describe and develop a prototype information model
- Evaluate the prototype against the ideal smart city information system

1.4. Research questions

Now that the topic of this thesis has been introduced and the objectives have been defined and described, relevant research questions can be formulated.

The main research question is:

What is the role of geospatial technologies in building smarter cities?

The research question is divided into several sub questions. These constitute:

What is the ideal smart city information system and what are its requirements?
How can available geospatial technology and data contribute to building smarter cities?
What is needed to build a prototype geospatial information model?
How does the prototype compare to the ideal smart city information system?

1.5. Relevance

This study is relevant for a number of reasons. It aims to clarify the smart city trend and make smart city design concrete by developing a prototype information model. It is addressed how smart cities and geospatial technologies may contribute to general quality of life and sustainability. For example, it can increase efficiency in public services and utilities by increasing collaboration between stakeholders. Stakeholders at every stage in the life cycle of buildings and other capital projects depend on information systems. From initial design concept to final demolition, spatial information plays a role, but communicating spatial information between systems is often problematic, and thus the systems frequently fail to deliver their anticipated value. Next to that, citizens can be informed by means of public and interactive maps. Geospatial technology can serve and assist emergency responses. And geospatial applications can increase efficiency in mobility and improve public transport systems. These are just some of the examples that can be shown.

Next to the obvious social and public relevance of this study, a scientific relevance can also be defined. From a smart city research perspective for instance, spatial information and geospatial technologies are often overlooked. This thesis aims to make a contribution to the smart city trend

From a practical point of view there is a need of a holistic approach to technology deployment in smart cities. Most cities cope with a proliferation of minor technology products and applications, mostly focused on a specific goal. Next to that, "openness" as a key technology design principle can help developers and users of technology see what works and what doesn't work. An open and free interface for example, can encourage low-cost, open-participation iterative experiments, testbeds and pilot projects that stimulate innovation and provide insight and guidance that can optimize for improvisation and resilience as well as prevent expensive IT failures (Percivall, 2015).

1.6. Research limitations

As with most researches this thesis brings along limitations as well. These are defined here and although they are interesting to research, they will not be part of this thesis. Instead, they can serve as topics that others can research in the future.

The concepts in smart city literature are discussed but it is not a deep dive into smart city theory, approaches and research challenges. Smart city theory is analyzed but this thesis does not contribute to giving new theoretical insights. Also, there is no judging on smart city approaches.

The focus in this thesis is not so much on the technicalities of the case study's 3D city model design. For instance, improving 3D spatial analyses relying on online 3D city model is not the goal. Also, improving collaborative city management and support decision making tasks relying on an (online) 3D city models. And improving urban planning processes relying on (online) 3D city models. Supporting urban planners to present their plans to the public and other stakeholders and giving the public the means to participate in urban planning processes are also not considered to be specifically relevant in this study.

1.7. Audience

This thesis is meant to give the stakeholders in the Smart Sustainable Districts project and others that are interested in the smart city topic an insight in smart city theory and applications, comparing these with GIS concepts and the concept of Spatial Data Infrastructures. It is specifically written for this audience, introducing them to the relation between smart city and GIS concepts.

Additionally, academics concerned with smart city concepts and/or GIS concepts can learn from a practical implementation of GIS tools in smart city development and understand the resemblance between the two.

1.8. Outline

The study begins with explaining smart city concepts, approaches, technologies and trends, standards, data, architecture and applications to underpin the conclusion of what the ideal smart city application might be. Then, the role and importance of spatial information in smart cities is discussed in chapter 3. This chapter also provides insight in geospatial concepts such as GIS, SDI, geo-standards, techniques and geospatial applications. In chapter 4 the case study is introduced, explaining the SSD project and the need of geospatial technologies in this project and what prototype has been chosen and why. Chapter 5 then describes how this prototype application can be build, what the requirements are, how data can be acquired, vitalized and visualized, which software is used and how the design process was done. Chapter 6 evaluates the case study, the design process and the outcome. Chapter 7 ends the thesis with answering the research questions, a discussion, a conclusion and some recommendations.

2. The Ideal Smart City Information System

This chapter aims to form a definition of the ideal smart city information system. It starts with a review on the smart city concept. Then the different approaches to the smart city concept are described. Section 2.3 gives an overview of current technologies and trends that are related to the development of smart cities. When this is clear, the current standards are mentioned, and it is argued what their importance is in smart city development. Next, (potential) data that can be gathered and used is explained before handling the concept of smart city architecture. Paragraph 2.6 gives an overview of the different kind of applications that can co-exist in a smart city. This leads to discussion and the definition of the ideal smart city information system in the conclusion.

2.1. The Smart City Concept

As was explained in the introduction, the smart city concept has evolved as an approach to cope with the challenges that have arisen in cities over the past decades and as result of the development in information and communication technologies (ICT). Although the smart city concept can be considered quite broad, several authors have tried to define what a smart city is, and which characteristics it has. In general, there is no widespread consensus on the meaning of a smart city and therefore it can be considered as a rather fuzzy concept (Witte & Geertman, 2017). This section gives an overview of the different interpretations and aims to clarify the definition.

Origins

The term 'Smart Cities' is not very new. It is suggested that it has its origins in the late 1990s, early 2000s (Harrison & Donnelly, 2011). Yin et al. (2015) argue that the term appeared in the early 1990s. Regardless of the exact time that the term started occurring in academic literature and other written works, it shows that the concept is relatively new when comparing it with other city planning concepts and approaches such as blueprint planning, synoptic planning and participatory planning. As it was a relatively new concept and as it involved a combination of urban planning and ICT approaches, it has attracted worldwide interest from companies, academic institutions and governments. These have all shed their view on the concept and have tried to name it in different ways.

Smart city characteristics

Many researchers have tried to generalize the characteristics of a smart city, often using overlapping terminology. Usually these characteristics are defined by looking at certain factors and indicators in several fields of activity.

One of the most widespread and accepted generalizations is the one by Giffinger et al. (2007). To define what a smart city is and what characteristics it has, a literature review was made by Giffinger et al.. Six characteristics are defined which may serve as a basis for the further elaboration of smart cities. These are smart economy, smart people, smart governance, smart mobility, smart environment, smart living. This definition of characteristics is also referred to as the 6-axes model and is widely used as a smart city approach. Section 2.2. will further elaborate on this model.

Other characteristics have also been identified by other academics. But as stated before, they often have overlapping terminology or use different wordings for basically the same concept.

Smart city actors/people

In the 6-axes model, one of the characteristics of a smart city is 'smart people'. People serve as actors and/or stakeholders in the smart city ecosystem. 'People' is a rather a wide concept though. In Giffinger's description people are the individuals in the city, instead of society as a whole. It relates to human and social capital and characteristics of people such as age, education, creativity and open-mindedness.

When defining actors or stakeholders in smart cities, people or citizens form a stakeholder group. Other stakeholders that have been identified in smart city research are for instance governments, businesses, academic institutions and utility companies, to name a few of the major groups. Business may have the goal to integrate systems, provide network services, vend products, or provide managed services (Frost & Sullivan, 2018). Governments may be municipalities, regional governments and national governments. Academic institutions can be universities, business schools, etc.

By describing the characteristics and various actors in a smart city, the environment in which smart city development takes place is described. But as there are many stakeholders in this environment, there are many definitions. The next paragraph gives an overview of these definitions.

Definition

With the increasing interest in smart cities came a wide variety of approaches and definitions and as of today definitions of smart cities are still emerging and there is currently no clear and consistent definition of smart city among the different parties (Yin et al, 2015). A common and broad definition is that with using ICT, cities could be more intelligent and efficient. Deakin & Wear (2011) list a number of factors that contribute to the definition of a smart city:

1. The application of a wide range of electronic and digital technologies to communities and cities
2. The use of ICT to transform life and working environments within the region
3. The embedding of such Information and Communications Technologies (ICTs) in government systems
4. The territorialization of practices that brings ICTs and people together to enhance the innovation and knowledge that they offer

But these factors can still be widely interpreted. Which specific ICT technology is meant or used, for instance? When defining smart cities using these factors and coming from a certain perspective or act as a certain stakeholder, one can define smart cities in multiple ways. Definitions range from focusing exclusively on infrastructure to definitions that stress citizen engagement and communities to act smarter. From a geomatics perspective for instance, a smart city is the full integration of a digital city, the Internet of Things and cloud computing technology (Li et al, 2013).

A holistic definition is presumably difficult to decide on (Hollands, 2008). This is particularly illustrated in a paper by Meijer & Bolivar (2016). They analyzed 51 academic papers discussing the smart city concept, resulting in a categorization of smart city definitions (figure X).

Figure X: 51 papers examined on smart city definition

Smart city as . . .	Focus	Number of papers
Smart technology in the city	Technology	12
Smart people in the city	Human resources	4
Smart collaboration in the city	Governance	6
Combinations of smart technology, smart people and smart collaboration in the city		12
No definition		17

Source: Meijer & Bolivar, 2016

Besides differentiation in defining a smart city there is also a differentiation in cities, so not one definition suits all cities. A smart city not just leverages new technologies, it is a complex ecosystem formed by multiple stakeholders such as citizens, government officials, companies, local industries, communities. It is composed of both *hard* (technological) and *soft* (social) aspects.

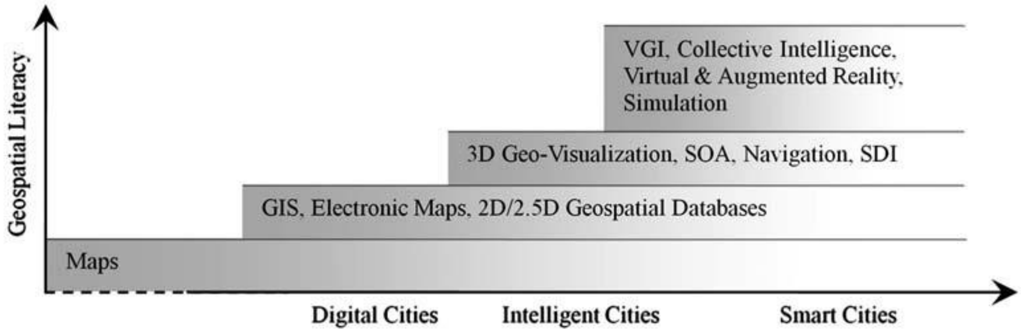
Next to the term smart city, other wordings have been introduced to refer to the use of ICT in modern cities. These include digital city and intelligent city. A digital city is a city that has its procedures, communication and information digitalized (Yin et al., 2015). When a digital city is extended with a layer of intelligence that can make decisions based on artificial intelligence, Yin et al. speak of an intelligent city. Derived from that, a smart city then is an intelligent city with applications that are directed towards practical use and user experience. Other terms that are used when referring to the definition of a smart city are for instance *connected city* and *real-time city*. Regarding this, the most encompassing definition to be found is the one by Roche (2014):

"*A smart city is a city that is able to efficiently organize technological innovations with the goal to anticipate, understand, discuss, act and serve many actors in its multi-faceted territory. A smart city operates in four dimensions:*

- *Intelligent city (social infrastructure)*
- *Digital city (informational infrastructure)*
- *Open city (open governance)*
- *Live city (a smart city is a living urban fabric that is continuously being reshaped and is adaptive to change)*

This definition breaks the smart city concept down into four dimensions and points out the different aspects that have to be taken into account when defining smart cities. A smart city thus is an intelligent city, as well as a digital, open and live city. One can also argue that without the concepts of digital and intelligent cities and the corresponding procedures and technologies, smart cities may not exist (figure 2.1). Although the underneath figure focusses on geospatial literacy, it gives an insight of the stacking of technological layers when moving towards smart cities. An argument might be that a smart city cannot be built unless there is a foundation consisting of digital and intelligent city concepts.

Figure 2.1: Geospatial literacy growth in modern versions of cities.



Source: Tao, 2013

Multiple definitions will continue to co-exist depending on one's perspective and discussion about what a smart city is will continue to prevail.

Approaches

There has been an ongoing discourse between academics involved with smart city theory on what the best approach is, and which instruments are needed to analyze, observe and research smart city concepts, as Harrison & Donnelly (2011) point out. These academics come from a wide variety of disciplines, which also confirms the broadness of the smart city concept. Among them are members of architecture, planning, engineering, transportation, utilities, information technology, operations research, social sciences, geography, environmental sciences, public finance and policy, communications, GIS, systems science. Next to academics, other stakeholders such as companies, communities and other institutions have developed approaches. Among these are technical and commercial approaches. The next paragraph describes the different approaches.

2.2. Smart City Approaches

Making cities smarter or assessing smart city concepts can be accomplished with a variety of approaches. These constitute scientific, technical and commercial approaches for instance. As this thesis is an academic work, the scientific approach will be described here, although technical and commercial approaches certainly may have some common characteristics.

Since the smart city term has been coined in the 1990s and companies such as IBM, CISCO, Microsoft, Intel, Siemens, Oracle, SAP (Kitchin, 2014) started initiatives to work with the term, (see for example IBM's Smarter Planet agenda (Palmisano, 2008)), the concept has continued to grow and evolve. This led to many initiatives where countries and cities started their own smart city projects, occasionally teaming up with companies. Also, researchers and academics shed their light on the subject and took a scientific approach. This may be a systematic, theoretical, or empirical scientific approach.

After approximately two decades of smart city concept research a preliminary balance can be made up. Multiple researchers have tried to generalize the smart city initiatives. Yin et al. (2015) for example, have defined two types of smart cities: (1) a data-centric smart city, (2) the multidisciplinary city. Next to that they have classified smart city application domains, after an extensive literature review (figure 2.3).

Figure 2.3: Classification of smart city application domains

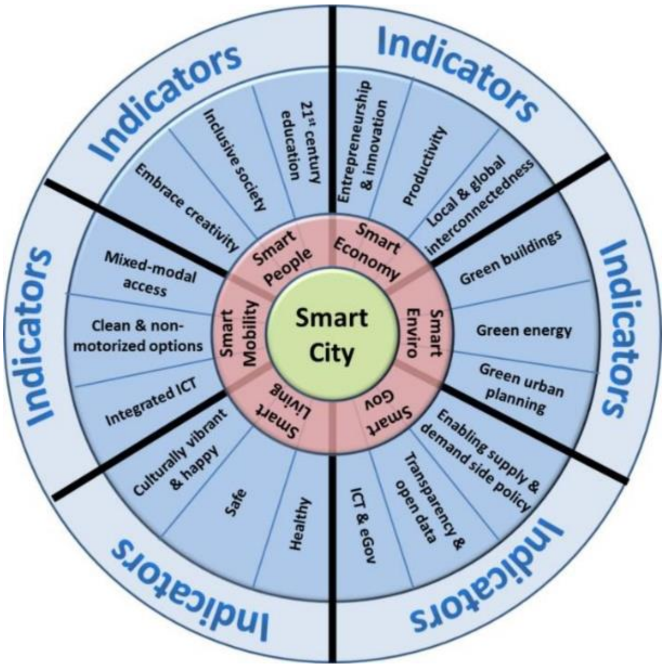
Domain	Sub-domain	Description
Government (more efficient)	E-government Transparent government Public service Public safety City monitoring Emergency response	Improving the internal and external efficiency of the government; enabling citizens and other relevant organizations to access official documents and policies; ensuring that public services work efficiently; monitoring and managing public safety; responding quickly and effectively in emergency situations.
Citizen (happier)	Public transport Smart traffic Tourism Entertainment Healthcare Education Consumption Social cohesion	Traveling and moving more efficiently; accessing contextualized, precise, real-time information in daily life; high-quality essential public services such as education, healthcare and sport; enriching spare time activities, communicating and sharing more with others.
Business (more prosperous)	Enterprise management Logistics Supply chain Transaction Advertisement Innovation Entrepreneurship Agriculture	Improving inter management efficiency and quality; using more efficient logistics and supply chain platforms and methods; advertising more widely and accurately; expanding trade partners and customers; facilitating entrepreneurship and investment; upgrading the business activity in a city, such as production, commerce, agriculture and consulting; fostering innovation.
Environment (more sustainable)	Smart grid Renewable energy Water management Waste management Pollution control Building Housing Community Public space	Delivering more sustainable, economic and secure energy and water supplies by taking into account citizens' behavior; using more green or renewable energy; recycling and treating waste efficiently and safely; reducing and preventing pollution in the city; offering mobility, telecommunication, information and all other facilities in different city spaces.

Source: Yin et al., 2015, p.7

Figure 2.3 shows the different domains of stakeholders in smart city development and the sub-domains that accompany them. A description of these sub-domains is also given. It is obvious that approaches from different stakeholders can be varied and thus a holistic approach, incorporating all sub-domains, can be quite a challenge.

Other researchers have proposed other approaches. An example of this is the 'Smart Cities Wheel' by Boyd Cohen (figure 2.4).

Figure 2.4: Smart cities wheel



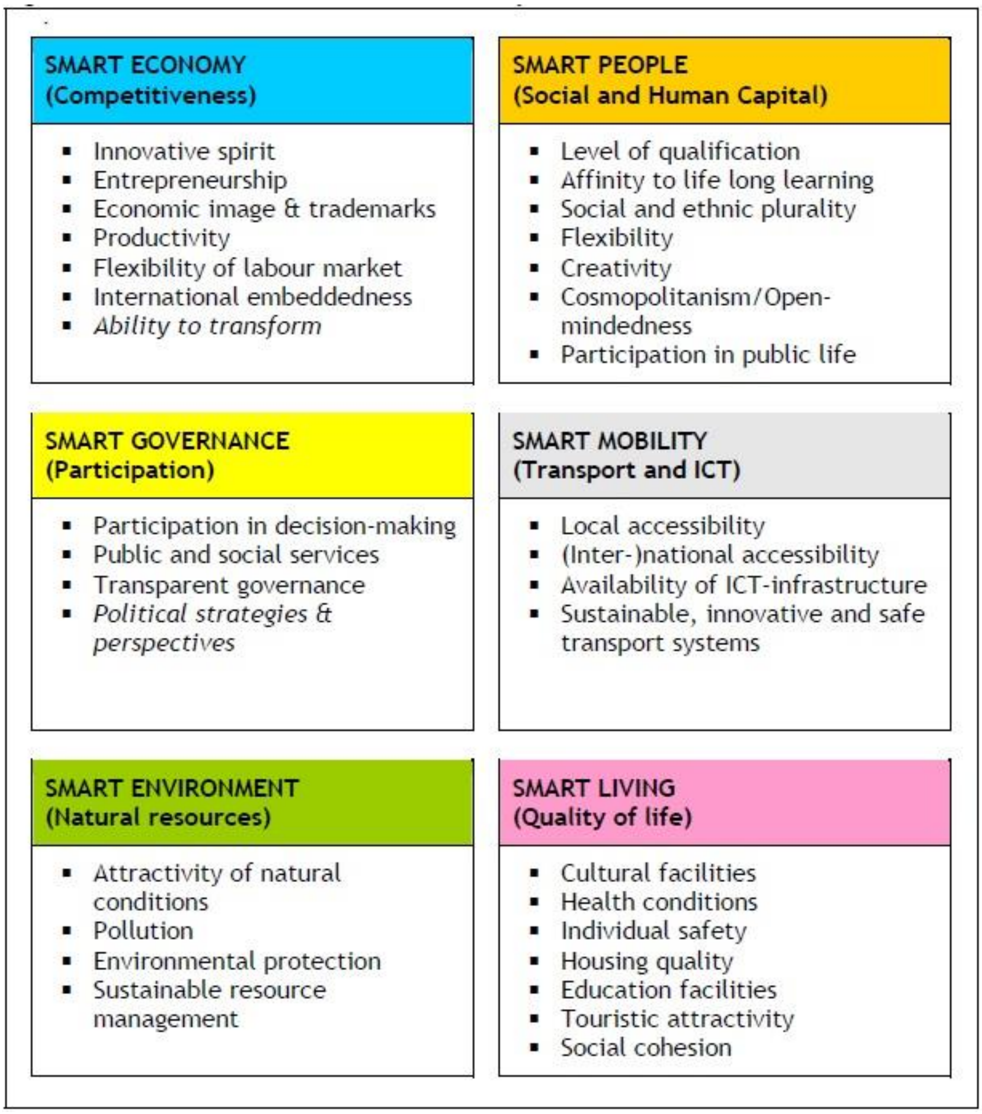
Source: Cohen, 2012

This is a model proposed to support smart city strategies and to develop processes. It relies on six characteristics which each have their factors and indicators. This is very comparable to the model of Giffinger et al. (2007), which was briefly described in section 2.1. and is further elaborated upon in the next paragraph.

6-axes model

The conceptualization of the smart city into six domains by Giffinger et al., gives a better understanding of the fuzzy smart city concept (see figure 2.5). This approach consists of defining specific indicators that can be used to measure the performance of a smart city.

Figure 2.5: Domains and indicators of a smart city.



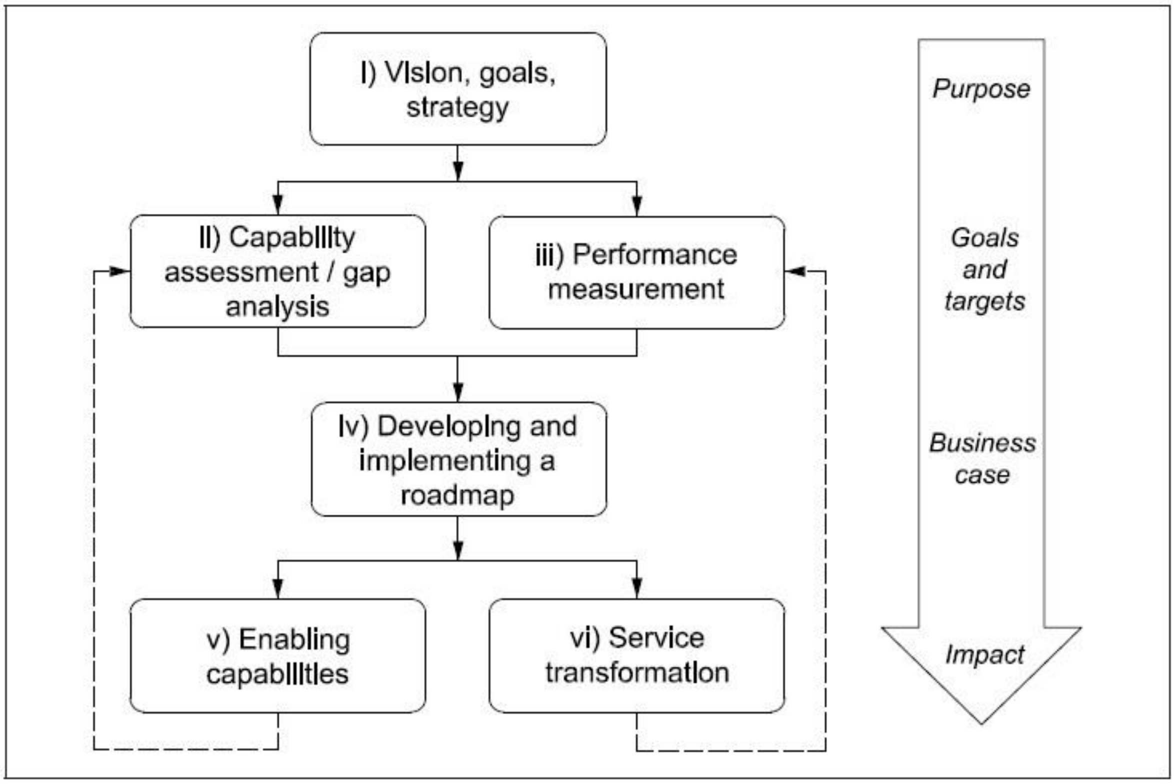
Source: Giffinger et al. (2007, p.12)

The above figure speaks for itself when discussing what is meant by these six characteristics. They each have factors that contribute to the characteristic. It shows what has been reviewed by Giffinger et al. (2007) and provides more specific indicators of what exactly can contribute to making cities smarter and on which indicators measurements should take place. Next to that, it provides a framework for discussing smart city concepts and what cities themselves feel is part of building smarter cities.

Other approaches

Besides an academic approach, other approaches involve systematic and commercial approaches. A more process-oriented or procedural approach for instance, is how to become a smart city and what steps are needed (figure 2.6). This is mainly a guideline for city leaders looking to move forward in the smart city agenda.

Figure 2.6: Smart city process framework



Source: The British Standards Institution (BSI), 2015

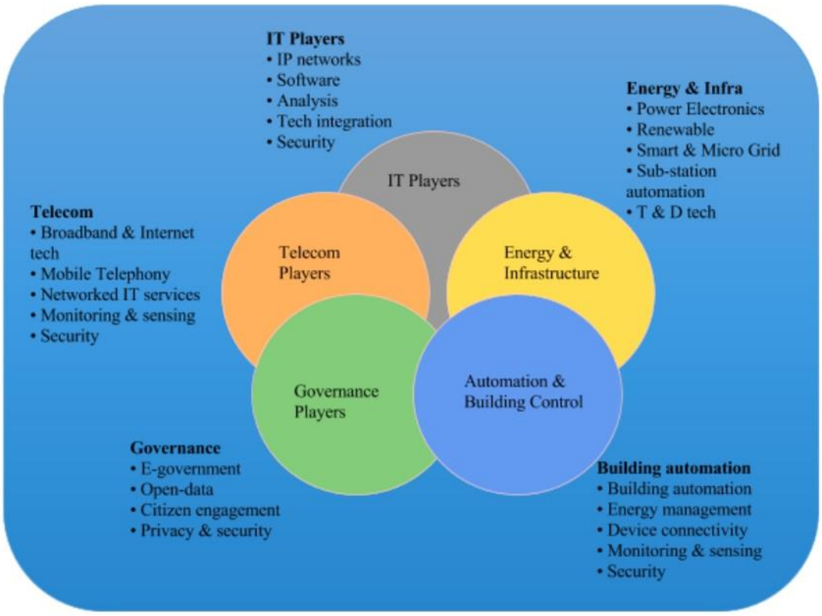
The approaches described here are merely a selection of a large number of different ways of coping with smart city development. Accompanying these approaches and partly depending on them are technologies and trends. The next section gives an overview of these.

2.3. Technologies and Trends

Now that several smart city approaches have been described, a closer look can be taken at the existing and emerging technologies and trends. Whereas section 2.2 focusses on the approaches and characteristics of a smart city, this section gives an overview of the most commonly used technologies that are used for data processes, such as data sensing, data vitalization, data mining and data visualization, for instance (Yin et al., 2015).

When looking at a smart city from a technological viewpoint, it can be argued that it is a complex ecosystem, made of up many technology areas. These technologies are often developed by minor and major companies in several technological areas and sometimes also complement and/or overlap each other. The goal of most of these companies, as they have a commercial drive, is to provide end-to-end solutions to a city's technological needs. Examples of these solutions are provided by companies such as SAP, Intel, IBM, etc. But due to the scale and size of most smart city initiatives, it is difficult to achieve this. Also, because companies must collaborate with companies from other technology areas. Lea (2017), has visualized this technological ecosystem which is made up of five key technology segments (figure 2.7). In part, this resembles the complex ecosystem of the different aspects in a smart city (see figure 2.2). In both ecosystem models, a holistic approach is required.

Figure 2.7: Technological ecosystem in smart cities



Source: Lea, 2017.

Specific and more general technologies for smart cities are developed by a broad number of ICT companies and are meant to support segments such as energy, transportation, urban planning etc. with the goal of creating smart 'solutions' to the cities and its citizens. The next paragraphs describe a few of these technologies and their impact.

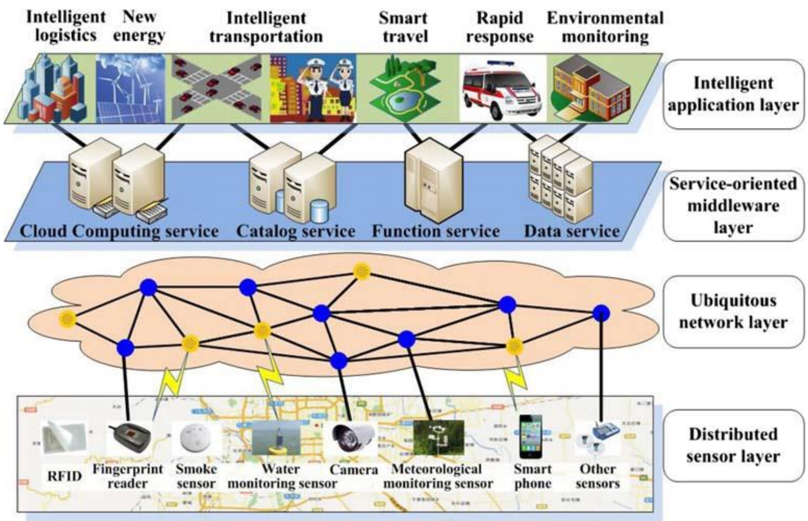
Networking and communications

One of the most important technologies is related to the underlying communications infrastructure. This infrastructure, consisting of for instance Low power WAN technologies, 3/4G networks and possibly 5G networks in the near future, enables smart cities to connect infrastructure, devices and people. It also plays a major role in gathering relevant data and delivering data services.

Internet of Things

Through the use of communication networks like internet and cyber physical systems, The Internet of Things (IoT), or Internet of Everything, has become trending. The technology and concept emerged in 1999 (Li et al., 2013). It refers to unique identifiable objects (things), such as infrared sensors, GPS, cameras and scanners, etc. and their virtual representations in an internet-like structure (figure 2.8). The IoT combined with cyber physical systems, defined as the connection and virtual representation of physical devices to the internet, is critical to the growth of smart cities (Lea, 2017). A prerequisite of implementing the IoT is that agreed protocols of information exchange and communication must be defined (see section 2.4 on standards and interoperability). Using the IoT cities can intelligently identify, locate, track, monitor and manage 'things'. It can also be used to gather large amounts of data which is considered as 'big data'. This concept will be described later.

Figure 2.8: A framework of a smart city based on the Internet of Things.

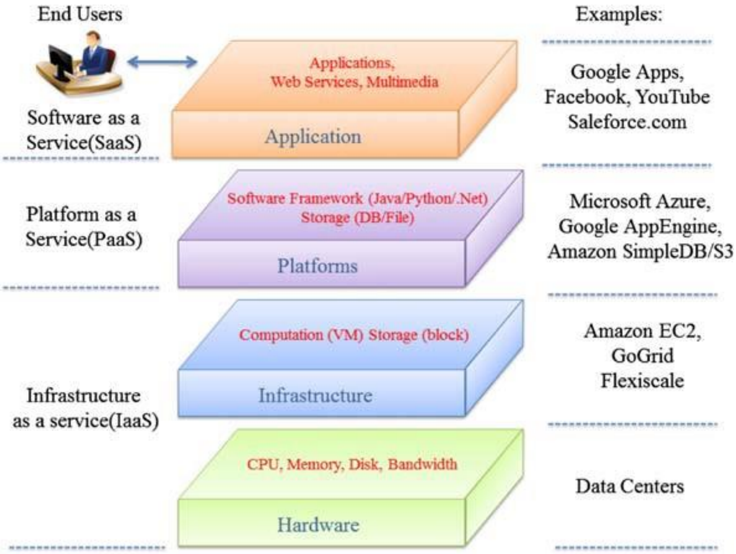


Source: Li et al., 2013, p.15

Cloud computing

Another emerging trend is computing 'in the cloud'. This is another information technology and refers to the access to data, software and hardware through a network like the internet. Data is stored in online storages (the cloud), as opposed to storing data on local hard drives and servers. From multiple devices (smartphones, televisions, laptops, tablets, etc.) people can have access to digital files and programs. Hence, people are not bound to a certain device or location to open the files. The recent developments in cloud computing has already had a huge impact on the development of smart cities. It affects how cities can deliver services to the various stakeholders in the smart city ecosystem. Examples of these services can be Infrastructure as a Service (IaaS), Software as a Service (SaaS), etc. (figure 2.9). In general, it is presumed that this reduces costs and improves efficiency.

Figure 2.9: A framework of cloud computing.



Source: Li et al., 2013, p.16

Open data

One of the most significant trends is the use and publication of open data. This involves policy to make governments and other public institutions provide datasets that are freely accessible. Many cities have already done so, and even (inter-)national parties follow up on this policy. This has resulted in the creation of open data portals through which anyone can request and query different kinds of data. Examples of open datasets are statistics about certain city-wide themes, city service levels, infrastructure data, etc. Although open data is not a technology by itself, it makes use of the other technologies discussed here and it also drives the use of these technologies.

Big data

Another trend is the one that involves the use of big data. Big data consists of data sets that are so large and complex that traditional data processing soft- and hardware systems are unable to cope with them. Typically, big data has the following characteristics: high volume, real-time, and coming from a wide variety of sources, having different formats and characteristics. It can serve for offering insights and economic value which can be used to efficiently improve the lives of citizens.

Citizen engagement

Another aspect of smart city technologies and trends involves citizen engagement. Although this is not strictly a technical aspect, it can serve for supporting the collection of (big and open) data, communication and dialogue between cities and citizens, and tapping into the collective intelligence of a community. It is rather the exploitation of available technologies to engage and communicate with citizens that is trending. This can be done in several forms. (Smart-) Phone or web applications make it able for citizens to report issues such as pollution, accidents, etc. Crowdsourcing data from citizens makes it possible to better understand the activities of the population. Hackathons and similar events can engage the technical community. And citizens can be put in the center as users in (co-)design processes. Finally, citizens can contribute to Volunteered Geographic Information (VGI). Perhaps the ultimate goal of citizen engagement is empowerment.

Digital cities

The last technology described here is that of digital cities. Although this technology is perhaps not one of the most well-known technologies, it is an important one as this thesis will present a prototype of such a digital city. In general, a digital city is a framework containing information to make sure that a city operates smoothly and orderly (Li et al., 2013). As such, it organizes data via unified coordinate systems (it makes information spatial) and visualizes this data in a map or a virtual 3D model of a city. This makes it easier for stakeholders to recognize patterns and discuss natural, social and economic information related to the physical real city. This thesis goes into detail about this specific technology later on.

The technologies and trends identified here play a major role in the implementation of smart cities and in the way citizens can be engaged in the process. But many other factors exist, including security, privacy, environmental sustainability, etc., that affect the development of these technologies. The next section explores the activities related to standards that are related to the technologies and the more general smart city landscape.

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2.4. Standards

To measure their performance in becoming smart, cities need metrics or indicators. Also, cities need a way to assess at which point in their development they are, in which direction they to head to, and measure their progress along the way. That is where standards come in. Standards are mostly international sources of best practices derived from experts from around the world. Many organizations have standardization as their main task. Some of the most known are for instance the International Organization for Standards (ISO), European Committee for Standardization (CEN), International Telecommunication Union (ITU, a UN body) and the International Electrotechnical Commission (IEC). There are standards for nearly everything. A common distinction that can be made is:

- Ad hoc standards
- Proprietary standards
- De facto standards
- De jure standards

This distinction has nothing to do with the sector or industry these standards have been developed in, but with their status or acceptance worldwide. Ad hoc standards being the least accepted and for which no formal body is needed, de jure standards being officially approved by international standard bodies (such as ISO). In between there are proprietary standards, which are usually standards of a certain company, and de facto standards, which are widely accepted but have no international and formal status yet.

In this discussion however, the focus is on IT standards, (such as standards for systems, hardware, file formats, protocols, programming languages, etc.), smart city standards (strategic, process and technical), and geo-standards (such as WMS, WFS, SensorThings, CityGML). These may have some overlap as for instance geo-standards also include standards for file formats.

Another distinction that can be made is the one between open and closed (or proprietary) standards. Open standards are open to the public and documentation is freely provided, allowing anyone to create software or an application that uses and implements these standards. Closed standards on the other hand are most commonly not available to the public and documentation is hard to get by, usually coming at a cost. They are developed by companies or other organizations that wish to sell and license the standard to other interested parties. Hence, closed standards can also be called proprietary standards. Examples of open standards are for instance the World Wide Web,

Because of the limited accessibility to proprietary standards, a trend can be noticed towards more use of open standards. This is also desirable to cope with the introduction of the

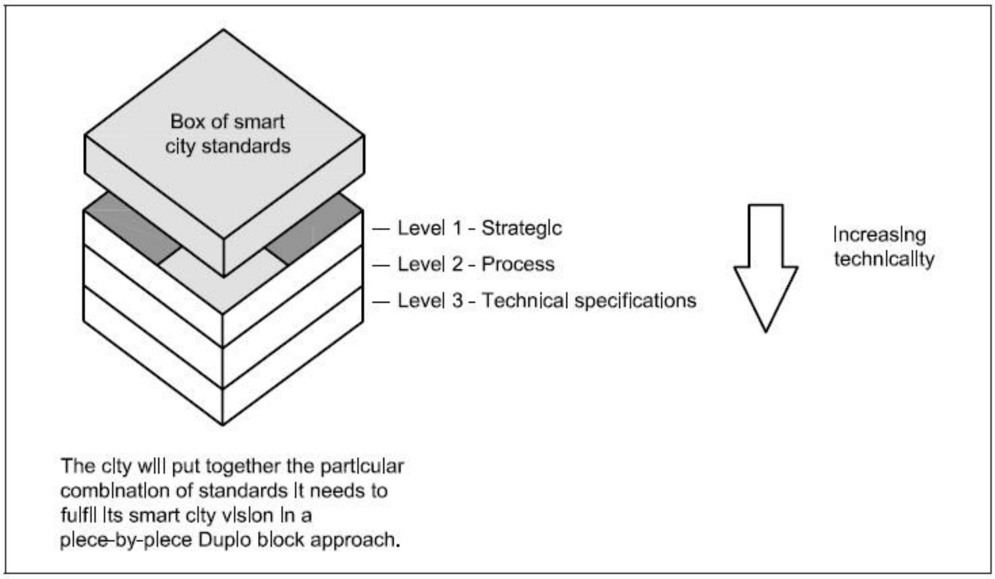
Internet of Things for example, as data is gathered from multiple sources which have different formats and characteristics. Open standards are needed for interoperability between systems (see page 25 for a brief description of interoperability), but also for efficiency, application innovations and cost effectiveness (Percivall, 2015).

Standards are critical for making cities smarter as they help to adopt new technologies such as the ones described in section 2.3. All these technological areas are somehow subject to standardization processes. Next to that, standards provide a trusted framework for cooperation with the various stakeholders in smart city ecosystems.

Smart city standards

For smart cities specifically, standards have also been developed (figure 2.10). Their role is to support the widespread adoption of approaches to the implementation of smart city products and services. Because of the breadth and scope of smart city initiatives worldwide, covering all domains (mobility, economy, people, etc.), many standards have been developed so far.

Figure 2.10: Levels of smart city standards



Source: BSI, 2015, p.21

An example of a strategic standard is the ISO 37120 Sustainable development of communities — Indicators for city services and quality of life. This standard identifies 100 indicators that cities should keep track of to monitor progress. What this standard basically does is defining methodologies for a set of indicators to steer and measure the performance of city services and quality of life (Percivall et al., 2015). The indicators for this specific standard are organized in the following themes: economy, education, energy, environment, recreation, safety, shelter, solid waste, telecommunications and innovation, finance, fire and emergency response, governance, health, transportation, urban planning, wastewater, and water and sanitation. In many cases, to measure their performance, these indicators need geospatial technologies and geolocated sensors to support their measurement, according to Percivall et al.. Not just to calculate and communicate measures for them, but also to support the enablement of planning, development and leadership in achieving the indicators.

Next to that, strategic standards give city leaders guidelines for identifying priorities and developing implementation roadmaps, leading to an effective overall smart city strategy. Process-level standards are more focused on how to manage smart city projects in a cross-organizational and cross-sectoral way, including how to handle finances. Technical standards are meant to address the technical requirements of smart city products and services to make sure they work and contribute to achieving results (BSI, 2015).

Benefits of standards

There is a reason that so many standards for different end-goals exist nowadays, especially for building smarter cities. They have many benefits, especially open standards. They enable integration between systems, enable integration between the physical and the digital, underpin common understanding (shared language and purpose), help to obtain funding, help to prevent vendor lock-in (making customers dependent on a vendor for products and/or services, unable to use another vendor without substantial switching costs) and enable scale (BSI, 2015).

Interoperability

Perhaps one of the most important things about standards is the interoperability aspect. This means that data that complies to standards that are commonly used, can be exchanged with (virtually) every node in the infrastructure and that data is readable on a number of systems (machine-readable). As smart cities consist of communication networks, information exchange is important. Interoperability makes cooperation between the various stakeholders in smart cities more efficient and effective. Open standards form a major part achieving interoperability.

Spatial domain (geo-) standards

Next to IT and smart city standards, there are specific standards for the spatial domain and technologies related to geo-information. Some of the main organizations developing these standards are CEN, ISO and the Open Geospatial Consortium (OGC). The next chapter discusses spatial information in smart cities. Section 3.4. discusses these so-called geo-standards in more detail. Most of these geo-standards are related to the above mentioned technical specifications (figure 2.10).

The next section discusses the importance of data in building smarter cities.

2.5. Data Challenges

Next to standards and interoperability, a major enabler of smart city development is the ability to exploit the power of data. City leaders, citizens, business and other stakeholders can make better decisions that better fit to their own needs when information gathered from data about what is happening in the city is accurate, timely and comprehensive. Next to that, data can support the overall functioning of the city. Before discussing architectural designs and ways to organize data in data management frameworks and/or data governance plans, it is also necessary to discuss what this data is (or can be) and what types of data may be gathered to incorporate in a smart city architecture. This section provides some examples of data that can be collected and discusses possible challenges and issues concerning these data. Figure 2.11, for example, shows possible data sources.

Figure 2.11: Potential smart city data

Data Category	Owner (Data Publisher)	Data Description	Sampling
Transport	Traffic Authority	Maps of Cities (Roads, Street Names, POIs, subway and bus stations, etc.) [3]	Static
	Municipality	Public Transport Schedules [4]	Semi-Dynamic
	Traffic Authority	Transport Authority Updates (Roadwork, traffic status, etc.) [5]	Dynamic
Air Quality	Env. Agency	Particle concentration [6]	Dynamic
Traffic	Traffic Authority	Number of vehicles passing between two points, speed [7]	Dynamic
City Events	Cultural Groups	Entertainment (movie/theater plays)	Semi-Dynamic
Municipal Services	Municipality	Library Data [8]	Dynamic
		Waste Collection Data [9]	Dynamic
	Private Company	Parking Meters [10]	Dynamic
Citizen data	Private Individuals	Social Media Information: Tweets, Status updates and blog posts, popular places ("check-ins")	Semi-Dynamic
		Household Energy Consumption	Semi-Dynamic
Health data	Private and Public	Relevant information about potential or confirmed sources of health threats	Dynamic

Source: Bischof et al., 2014, p.2

In the figure above the sampling column describes the periodicity. Static indicates that data is not updated automatically but has to be provided manually. This type of data is usually used as reference. Semi-dynamic means that it is updated on a regular basis (e.g. weekly, monthly, annually). Dynamic means that the data is continuously updated and might even be in real-time when collected by sensors for example.

Challenges and issues

As the data collected in smart cities and the data sources are heterogeneous, it provides challenges to process this data. Usually, data is aggregated and filtered before transferring or incorporating it into smart city information systems. A requirement here is that after the data processing, the data is available in an interoperable format. Also, data should be findable and accessible through query and publish facilities. It can then be used to be integrated into services and applications by the stakeholders. The main challenges that this process provides concern data quality, privacy, security, complexity, interoperability, volume and integration (Bischof et al., 2014).

The next section goes into more detail about how this data process can be designed by mentioning smart city architecture.

2.6. Designing Architecture

As smart city projects involve ICT processes, they need guidelines, as is the case with most ICT projects. In ICT, these guidelines are referred to as architecture. Such an architecture provides for understanding how to use technologies to conceive and implement a smart city project. Hence, ICT architecture for smart cities can be called smart city architecture (Yin et al., 2015, p.7). However, as is the case with the smart city concept in general, there is still a wide variety of definitions proposed by different parties. Next to that, there are many ways of how smart city architectures can be designed. Multiple researchers have done so and have proposed different approaches and have described some common requirements that smart city architectures should have. The next paragraph describes these requirements, before delving into the components such an architecture should have.

Requirements

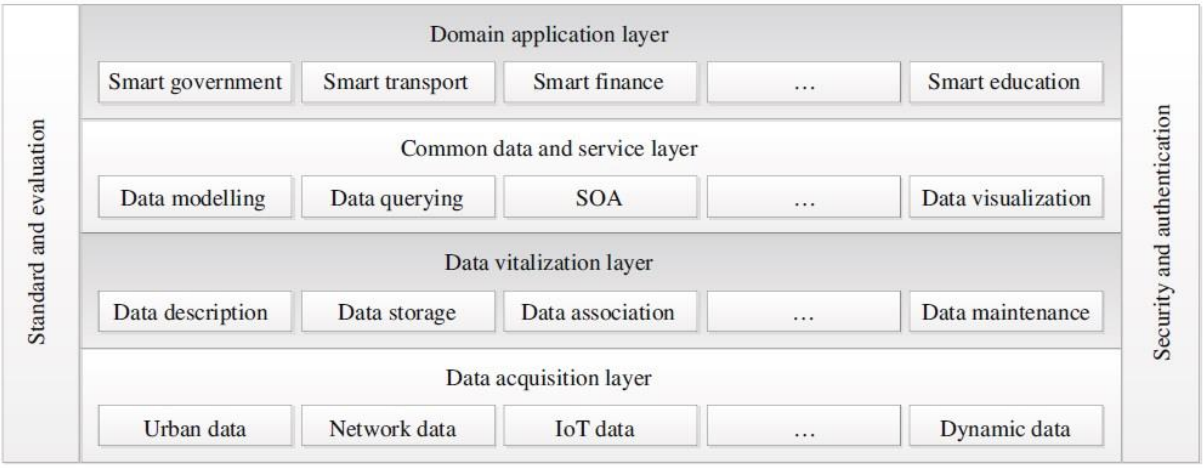
Before designing a smart city architecture, a city can define requirements. These may involve "openness" as a key technology design principle that helps developers and users of technology see what works and what doesn't work. An open and free interface for example, can encourage low-cost, open-participation iterative experiments, testbeds and pilot projects that stimulate innovation and provide insight and guidance that can optimize for improvisation and resilience as well as prevent expensive IT failures ((Percivall et al., 2015).

On the other hand, a requirement can be that a proprietary platform is chosen. These may be provided by one of the major vendors of smart city technologies which are mentioned before, such as IBM, SAP, Microsoft, etc.

Architecture components

The following paragraphs describe the main components of a smart city architecture. These are still quite generic and for each city it may differ depending on the available technologies. The main components are distilled from a broad range of smart city architecture literature. Yin et al. (2015) for instance, have provided a smart city architecture proposition (figure 2.12).

Figure 2.12: Smart city architecture proposition



Source: Yin et al, 2015, p.10

Besides the mentioned layers and components in the above figure, an overview of the main components is described here in more detail.

- *Data sources/technology and infrastructure*

One of the main components of a smart city architecture are the data sources. This includes connectivity to open (standard) networks (e.g. BlueTooth, LORA, WIFI, etc.), devices that can be used as data source (e.g. air quality sensors, mobile phones, cameras, etc.) and the connectivity to proprietary networks such as utility networks or mobile networks.

- *Data infrastructure/management*

When data sources are defined and are known, it is necessary to make a data governance plan and create a data management framework. This includes the processing and storage of data. This can be any kind of data such as open data, historical data, big data, geodata. Next to that it must be defined what the data quality will be, how complex event processing can be organized, which data models (e.g. Fiware, USEF, CityGML) should be used. Also, data search indexes can be organized.

Next to creating a data management framework, it is needed to define security and privacy settings. These constitute for example identity management, authentication, privacy policies, security management, authorization and access management. This make sure that the ability to quickly access data is taken care of, in a secure and private way.

A third part is platform management. This is made up of services lifecycle management, device and asset management, monitoring and legging, and orchestration for example.

- *Data services*

On top of a data governance plan, data services can be built. These are for example services catalogues (ontology, metadata, registry), developer support (documentation, examples, sandbox), API management (billing, monitoring, security), and API provisioning (open data, smart city/sensors, REST/JSON, library).

- *People/citizens/users/actors*

Next, a major component of smart city architecture are the stakeholders, composed of people, citizens, actors, users, etc. This group has to interact with the architecture and can provide valuable input for the functioning of it. Also, people can connect with each other, can be engaged in the process, can develop applications etc.

- *Applications*

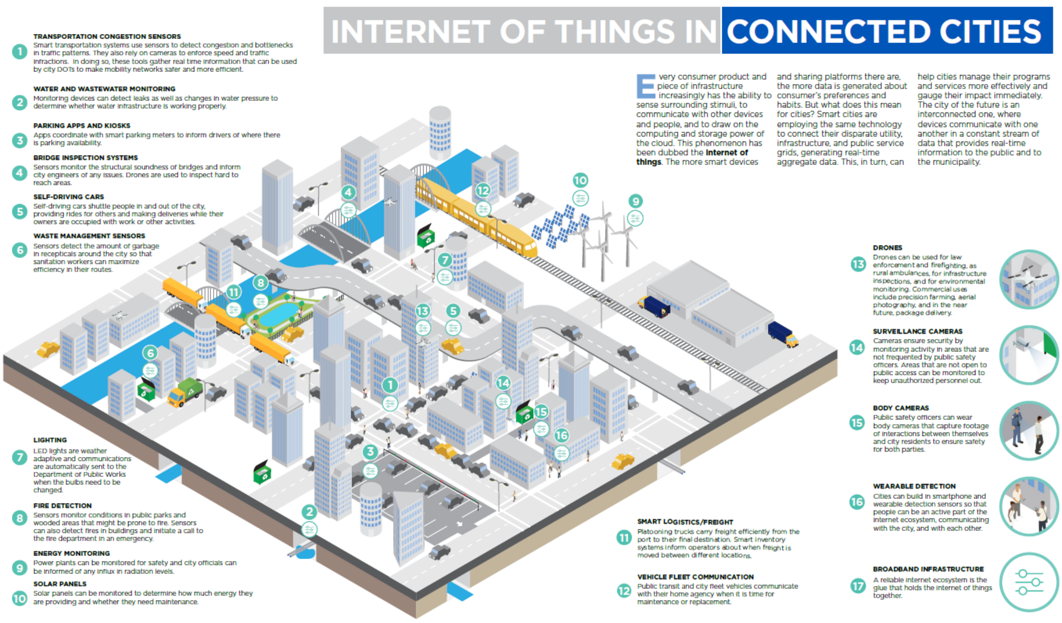
When data services are established, applications can be built. These can be domain specific. The next section (2.7) describes these applications in more detail.

2.7. Applications

This paragraph describes a selection of different kinds of applications. Applications are generally the incentive for building smart city information systems. An application can be anything that uses data and data services to provide a solution or insight in current problems and development. Typically, it's a computer program or software that can help users perform certain tasks, functions or activities for the user's benefit. It differs in that way from the application of a smart city concept as a whole.

On top of the domains described in section 2.2. and resulting from already implemented actions, applications can be built to achieve results. These make use of the available technologies, data services and architecture in smart cities and can co-exist. They can be built with the help of sensors for instance, which increasingly are used to communicate with other devices and people, and to make use of the computing and storage power of cloud services. The sensors can be regarded as being part of the Internet of Things (IoT). Some practical applications constitute water and wastewater monitoring, parking apps, bridge inspection systems, energy monitoring and vehicle fleet communication, to name a few (figure 2.13).

Figure 2.13: Overview of smart city applications



Source: National League of Cities (2016, pp. 8-9)

Other applications that are defined by several academics are for instance: utilities (smart grid, smart water, etc.), sanitation, intelligent buildings, intelligent transportation, health, public safety and security, environmental protection, emergency services, education, urban planning, and open data (Percivall, 2015, p.9). Or smart economy, smart mobility, smart environment, smart people, smart living and smart governance (Gruen, 2013) and smart municipal supervision, smart transportation, smart environment monitoring, smart tourism (Li et al., 2013).

As can be analyzed from this, there is a wide variety of applications possible. There is also some overlap in what the application is meant for in the end (its goal). Different wordings are used for the same type of application. This might make it difficult for people working in smart cities to distinguish between them or might confuse.

The next section discusses what the ideal smart city information system should consist of and what potential benefits and risks there are.

2.8. Discussion

To discuss what the ideal smart city information system is or should consist of, all aspects in smart city development must be looked upon. Ideally, such an information system should incorporate all aspects. In general, an argument is that it should connect people to city data and that a city provides (smart) data services so that people can use the data or applications can be developed. These data services are for instance (open) data catalogues with the option to use or download (raw) data. Other services may include the provision of Web Feature Services (WFS) when spatial data is regarded.

However, the data in smart city information systems can be quite complex and not understandable for everyone. Therefore, a requirement may be that raw data (such as satellite data, aerial pictures, etc.) should be made insightful for urban planning and decision-making by means of providing understandable products for laymen such as dashboards, maps and other communication tools. Next to that it should have the possibility to design meaningful solutions, streamline management processes and transform (spatial) data into actionable intelligence. However, a distinction should be made here between sectoral and integral applications. Sectoral apps are typically designed for a certain end-goal such as waste management, utilities, transportation etc. Integral apps try to incorporate all smart city domains of the 6-axes model of Giffinger et al., for instance. These domains can then be monitored, controlled, optimized in a single dashboard. Other requirements that the ideal smart city information system might have refer to data redundancy, well-specified data semantics, interoperability, extensibility, functionality and transferability. Also, one technology was named digital cities, or a 3D model of a city. This technology can serve as a backbone of a smart city, incorporating all other technologies. Such a model requires spatial information. Next to that, smart cities require standards that enable data and apps to easily interoperate, but this requirement is often overlooked. A start can be made by developing a district- or citywide 2D and 3D urban data model to integrate different sources of available (geospatial) data. This data model then becomes the city's open standard, a language that all stakeholders/actors, datasets and technologies use to interact.

Potential benefits

The benefits of making cities smarter can be generalized but be different for various stakeholders. For citizens for instance, some of these include better personalized services, access to information, greater transparency and it supports collaboration and helping each other more effectively. For businesses these are more efficient management and new business opportunities. For service providers they are greater synergies, individualized service offerings, and new ways to meet customer needs. For governments and city leaders the benefits may be more informed decision-making, facilitation of wider service provision, better collaborative processes, better citizen engagement, and more positive relationships with other cities (BSI, 2015).

Potential risks

Risks or negative aspects can also be identified, as is common with emerging concepts. A major risk for instance is financial risk. Smart city initiatives require funding for the implementation of new technologies (e.g. the placing of sensors). As this implementation might be complex, there are risks of substantial losses.

Another major risk which is on the agenda of cities, governments and companies at this moment is privacy. Ethical and legal issues play a role in this. Personal information might fall into the wrong hands and privacy might not be guaranteed due to the complexity of smart city systems. Security is an issue here, as malicious hackers can take benefit of failing systems.

Another risk may be the power of companies involved in smart city development and the corresponding dependency of cities on these companies' technologies.

And last but not least a risk is that society is becoming an algorithm by increasingly using apps like AirBnB, Uber, Facebook, Tinder and other (social) media. A rather disturbing (although still mostly fictional) insight in this development is given by the Netflix series 'Black Mirror' for example, that promotes the possible negative aspects of (future) technology.

These potential benefits and risks form an interesting discussion point but are not in the scope of this research. It also depends on which approach is taken towards smart city development for which benefits and risks there are eventually.

2.9. Conclusion

This chapter discussed smart city concepts, approaches, technologies and trends, standards, data, architecture and applications. To conclude it is argued what makes a city really smart and what the value of a smart city is. Also, how a definition of the ideal smart city information can be formed.

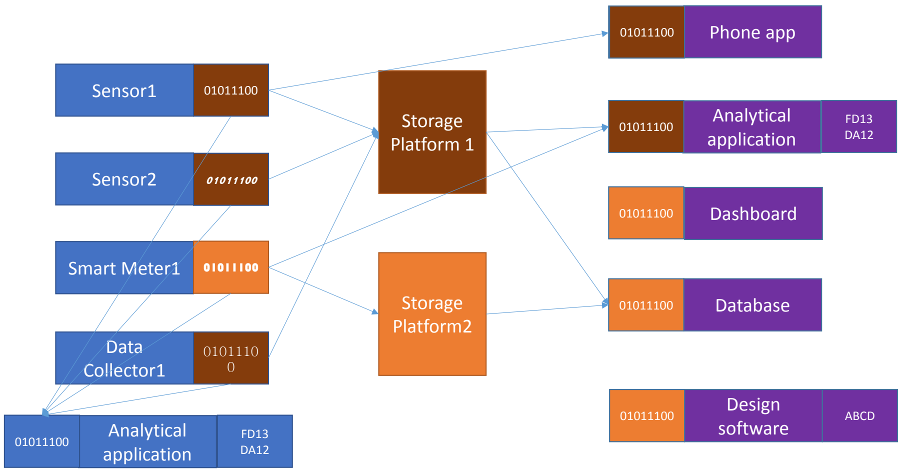
To decide when a city can be called 'smart', a reference is made to the before mentioned 6-axes model by Giffinger et al. (2007). The elements, smart economy, mobility, environment, people, living and governance must be in balance. In other words, sustainable economic development and improving the quality of life must be fueled by strategic investments in human and social capital, (new) ICT technologies, mobility and communication infrastructure. This being done by wise management of natural resources through participatory governance (Gruen, 2013).

Another way of defining smart in this sense is looking at how developments can take place. The smartness of a city does not involve the existing or implementation of technology as such, but how technology is used, as part of a wider approach to helping the city function effectively, sustainably and resiliently (BSI, 2015). The same argument is proposed by Lea (2017): technologies to solve problems can exist, but the human and institutional aspects should be taken into consideration. The goal of a smart city is to create value for the entire system it is situated in. This value can be added to any of the domains in the 6-axes model (economy, mobility, people, environment, living, governance). It can be assessed in both quantitative and qualitative ways.

To finally come to a definition of the ideal smart city information system and what its requirements are it is proposed that it should be able to measure indicators of smartness, as is proposed in multiple approaches. This requires a stable information architecture which is interoperable, functional, extensible, secure, and transferable which should be able to incorporate different technologies such as IoT, networks, cloud computing, open and big data, citizen engagement, digital cities etc. using (open) smart city standards. If this is the case it can serve as an ideal basis for the development of specific applications. Open standards are needed for interoperability between systems, but also for efficiency, application innovations and cost effectiveness. Next to that, smart cities require a framework of trusted/authoritative data; for example, core reference data in 2D and 3D (i.e. topography), identifiers and addressing, smart infrastructure (BIM, smart grid), and sensor feeds (Percivall, 2015). These are types of spatial information that are crucial for building smarter cities. Also, the openness to different data types, such as volunteered, unstructured and linked data is wishful. Such a framework, based on spatial information, needs a data integration platform, which is provided, in part, by OGC City Geography Markup Language (CityGML).

More practically, an overview is given here of a smart city information system ecosystem. In order to provide valid digital solutions for urban development, urban planning scenarios, etc. a lot of data representing different contexts, validity, entities and / or scales are needed. Those kinds of data exist (see figure 2.14) but are not accessible due to incompatible formats and typically not offered as service. Moreover, the meaning of provided data or datasets is usually unclear to non-domain users. However, these data are needed and requested in order to do valid planning in a complex system like a city. Even if the location and the meaning of the data is clear to the user, managing and / or analyzing applications are not present to the user.

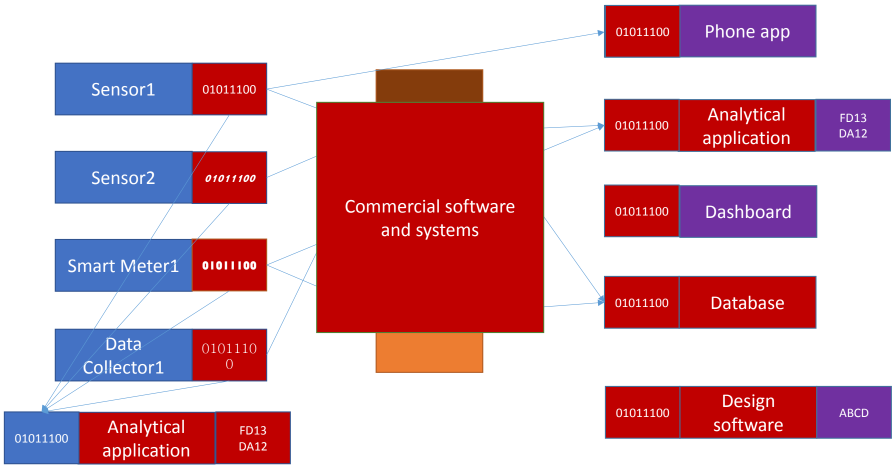
Figure 2.14: Example for pockets of data and systems in a city (technological ecosystem)



Source: TUM, 2017

There is a specific need in all kind of applications, planning scenarios, etc. in a city to easily discover data, data providers and applications. Data coming from sensors or smart meters (JSON, XML, CSV, TXT), human observations (CSV, TXT), simulations (XML, JSON, TXT), analysis (XML, CSV, TXT, JSON) and services (WFS, WMS, SOS, etc.). Standardized interfaces exist but are typically not present to the administration or authorities, since current commercial solutions gathering such kind of information require high capital input, have the risk to lock one in industrial solutions that are not compatible with other systems, or require the exchange of existing systems – all of these coming with high costs (see figure 2.15).

Figure 2.15: Example how systems would have to be brought together by using one commercial solution forcing everyone to change

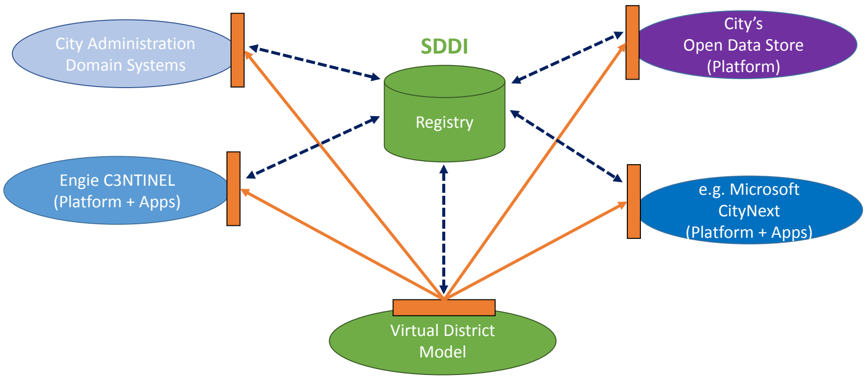


Source: TUM, 2017

This chapter has outlined the currently available solutions and approaches. To meet the needs described above and to implement a smart city information system, one would have to convince all different stakeholders to acquire, implement and migrate to one type of software/hardware solutions. This is not likely to happen as the various industries and operators have been working with their systems for years and are bound due to high sunk costs. Hence, instead of replacing existing systems, a solution that works with these existing systems can be developed. It is an additional layer, that is put in place in parallel to the existing systems, and that is able to communicate with all the systems that are already in place. Additionally, it is based on open standards, and due to the integration of a virtual district model that links all kinds of data sources and users to real objects in the city, much more accessible and intuitive in its use.

As was mentioned in the introduction already and later in this thesis as part of the case study, this additional layer is part of the Smart District Data Infrastructure (SDDI) concept.

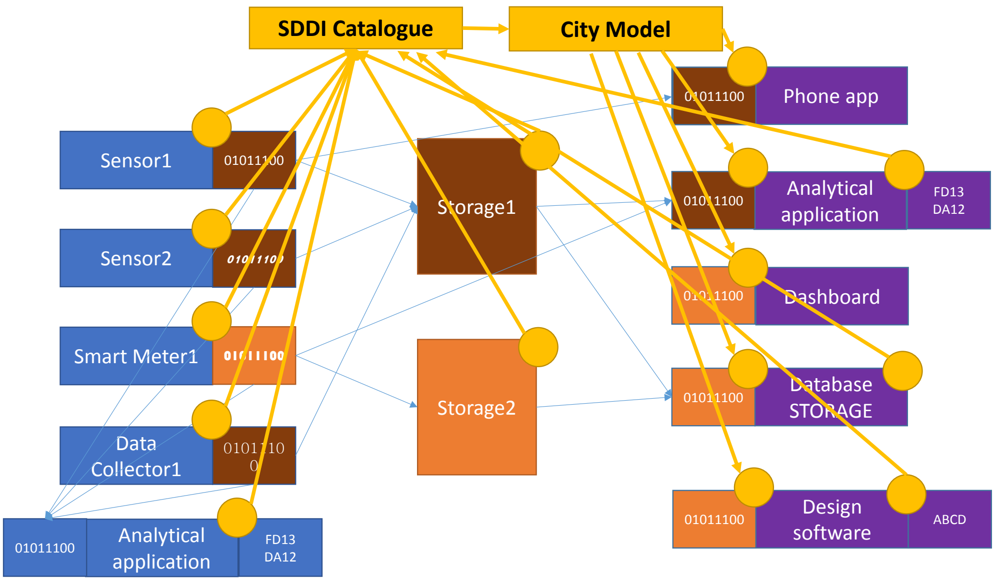
Figure 2.16: The SDDI concept



Source: TUM, 2017

While figure 2.16 illustrates the basic general concept of this additional layer, figure 2.17 shows the incarnation of this additional layer in the example provided in figure 2.14.

Figure 2.17: Example of the implementation of SDDI to the systems illustrated in Figure 2.14



Source: TUM, 2017

As is outlined above, instead of replacing existing software, hardware and communication structures, this solution builds on them, supplements them and is implementable without having to overcome institutional barriers. As a result, it is highly cost-efficient for every stakeholder in a city. One thing to point out at this place (figure 2.17) is that the outputs of the various applications and tools can be also made accessible through the SDDI, meaning that in the long-term future this solution can lead to a district operation based upon many real-time feedback loops, using the best software and solutions that are out in the market.

For the sake of clarity and to later compare the prototype developed for this thesis, the specific requirements of an ideal smart city information system are listed here, with in between brackets specific indicators:

- Facilitating the organization of the data, applications, services, sensors of a city in a common framework and technological ecosystem (*clear and stable architecture*)
- Low entry barriers / low investment risks / high flexibility
    - low operation costs (*open source and flexible software)*
    - no migration costs, because existing systems and platforms are interfaced
    - easily and incrementally extendible: datasets, applications, services, and tools can be added and used anytime and by third parties (*open standards/open access*)
- Facilitation of easy and user-friendly access to city resources (*dashboards, maps and other communication tools*)
    - to the customer and its partners; also to the public (practical use and user experience) (*webportal for communication, citizen engagement)*
    - accessibility to (geo-)data and information (*online data catalogue with download option)*
    - Providing an intuitive 3D geographic view onto the city resources (*3D webviewer*)
    - User clients incl. 3D visualization run on any platform, operating system, and browser without extra installations; incl. mobile systems (*domain application layer*)
- Support of planning and decision making
    - Visualization of newly planned buildings in the geographic context into a Virtual District Model (*digital twin*)
    - Facilitation of urban simulations like solar potential analysis, building energy demand estimations

The next chapter discusses the role of spatial information in smart cities and gives a further insight in Geographic Information Systems (GISs), Spatial Data Infrastructures (SDIs), geo-standards (in particular CityGML), supporting techniques and geospatial applications.

3. Geospatial Information and Technologies for Smart Cities.

Now that the smart city concept and its multiple aspects has been discussed it is necessary to discuss the role of spatial information in smart cities. Deriving from smart city literature, this is often an overlooked item. In fact, this thesis argues that spatial information and geospatial technology is central to providing a (technology) platform that forms the backbone of a smart city (e.g. Gruen, 2013; Percivall, 2015; Penn & Sayed, 2017).

This chapter explores the concepts related to spatial information and geospatial technologies and how they can be integrated in smart city development. It starts with discussing spatial information from a smart city literature perspective. Then, the concept of Geographic Information Systems (GIS) is explained and how it can serve as smart city platform or be part of wider Spatial Data Infrastructure (SDI) which is described in section 3.3. Next, an overview is given of so-called geo-standards which make it possible to exchange data and information with a geographical component in a digital and unambiguous way. When this clear, the supporting geospatial techniques are described, leading to an overview of geospatial applications that can be of use in building smarter cities in section 3.7.

3.1. Spatial information

Several authors have tried to underline the availability and importance of spatial information and data in smart cities. Harrison & Donnelly (2011) mention GIS as they try to structure and classify the many different types of information that are generated in cities in an Urban Information Model (figure 3.1). They claim such a model is often developed with the help of a Geographic Information System, which makes perfect sense if one looks at the layering of groups of information. This resembles the layering of data sources in most GISs. However, Harrison & Donnelly mention that for instance social networking tools are developing another approach to the Urban Information Model and are taking it in new directions.

Figure 3.1: Urban Information Model

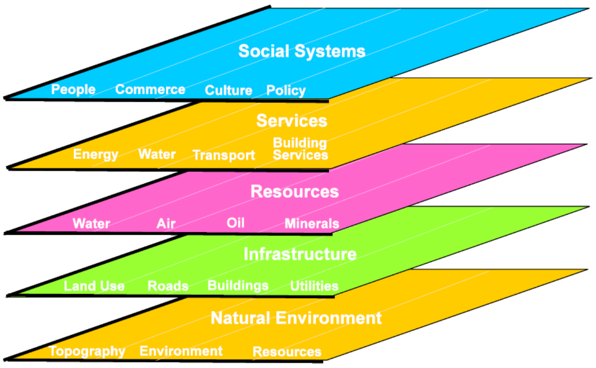


Figure 1: A simplified view of the Urban Information Model. Each plane represents a group of layers containing different, but related, types of information about the two-dimensional space.

Source: Harrisson & Donnelly, 2011

GISs play an important role in smart cities when it comes to data visualization. When presenting data towards end users of a smart city, which can be citizens, companies, governmental institutions etc., data visualization can show complex urban information in a simple and direct way, hence establishing interaction between users and data. One of the most common ways to achieve this is by using GIS visualization (Yin et al., 2015). However, as the data in smart cities often are big data, there is a challenge to be overcome to (re-)present it in a user-friendly manner.

When reviewing the academic discourse on how GIS technology fits into the smart city concept, there is little to be found. This seems to be a subject of research that still has to be developed. There is a lot to be found on Spatial Data Infrastructures (SDI) which show resemblance with smart city information systems. What can be found on GIS and smart cities is for instance that some academics argue that creating a smart city through proper planning of utilities and infrastructure cannot be achieved unless GIS technology is enabled and an SDI is established (Al Hashmi, 2016). Roche (2014), points out that geospatial subjects and references form a minor component of discussion in municipalities for instance. Reports on implementing smart city initiatives show that issues involving scale (geographical and administrative) in municipalities are included. They also make clear that a need for spatial analysis and research prolongs or starts to emerge. Additionally, explicit GIS methods and tools are needed. So, especially in professional or governmental reports concerning smart cities there is little or no reference to GIS and SDI (Roche, 2014).

Spatial information framework for smart cities.

The issue of a lack of research on spatial information in smart city literature is also illustrated in a White Paper written by members of the Open Geospatial Consortium (OGC) with the title 'OGC Smart Cities Spatial Information Framework' (Percivall et al, 2015). In this paper they claim that location is a primary method for organizing smart city services (figure 3.2) but that this is often overlooked. They also argue that building a model of the urban environment using CityGML is a first step towards the deployment of many additional functions. Building such a model forms the case study of this thesis.

Figure 3.2: A smart city uses location as an organizing principal to benefit residents, visitors, and businesses of all types.

Source: Percivall, 2015.

3.2. GIS – A Platform for Smart Cities

Because of the presence of location factors in smart cities, a method to organize smart city aspects as described in chapter 2, is using Geographical Information Systems (GISs). In short, a GIS can be used as an atlas (or rather interactive maps on computers), which offers many functionalities. It works with layers of (spatial) information that one can turn on and off. Each layer contains data and can be visualized as a map of an area or location. Hence, information is linked to location. This is the main strength of a GIS. When this linkage is established, information can be requested, added, combined, analyzed, and visualized.

Another strength of a GIS is that spatial data can be manipulated through an operation called geoprocessing. Such an operation requires the input of dataset and a tool to run the process on that dataset. This results in an output dataset on which one the following geoprocessing operations have been used: geographic feature overlay, feature selection and analysis, proximity analysis, topology processing, raster processing, and data conversion. These are some of the most common tools.

Next to desktop GISs, many other types of GIS software exist. These include web map servers, spatial database management systems, software development frameworks and libraries for both web and non-web applications, cataloging applications for spatially referenced resources. All have different functionalities Figure 3.3 gives an overview of the different tasks that can be accomplished with different kinds of software.

Figure 3.3: GIS tasks accomplished with different GIS software.

● standard functionality, ○ optional functionality.

GIS task vs. GIS software	query/select	storage	exploration	create maps	editing	analysis	transformation	creation	conflation
Desktop GIS									
- Viewer	●	●	●	○					
- Editor	●	●	●	●	●		○	●	
- Analyst/ Pro	●	●	●	●	●	●	●	●	●
Remote Sensing Software		●	●	○	●	●	●		
Explorative Data Analysis Tools	●	●	●	●	○	●	●		
Spatial DBMS	●	●				○	●		
Web Map Server	●		●	●	○			○	
Server GIS / WPS Server	●	●		●		●	●		●
WebGIS Client									
- Thin Client	●		●						
- Thick Client	●	●	●	●	●	●		●	
Mobile GIS	●	●	●		●			●	
GIS Libraries		●		●		●	●		●

Source: Steiniger & Hunter, 2012

Some popular products that GISs can produce are for instance digital road maps, height contour maps, digital height models (e.g. DTM, DSM), topographical maps, thematic maps, satellite images, geological maps, to name a few. But also, 3D city models as will be shown in the case study.

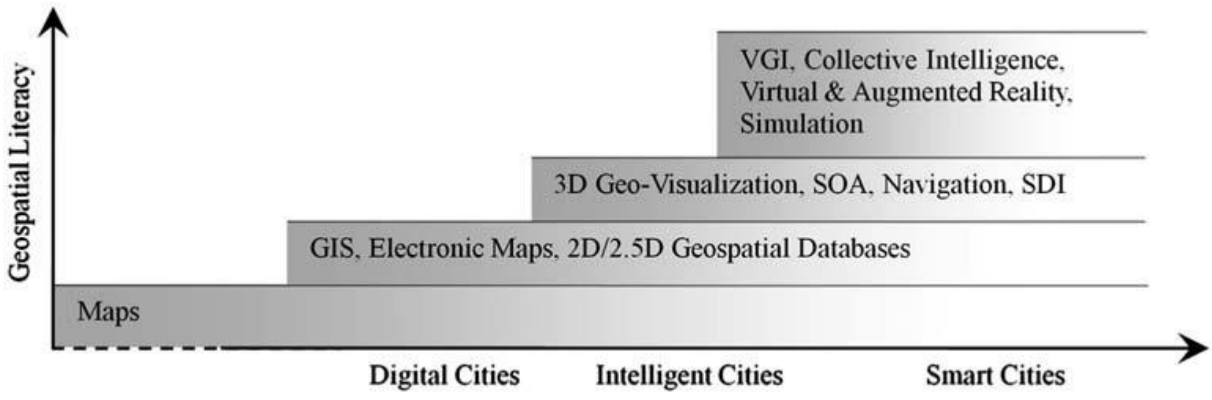
GISs are increasingly used in companies and governments as a more modern method to support spatial analyses and contribute to decision-making in the living environment. The next paragraph describes how GISs can be implemented in smart cities.

Implementing GIS

When looking at the specific use of GISs in smart city concepts and development, it can serve as a centralized information system that provides an IT framework which may integrate stakeholders, technologies, standards and data. But also, other aspects of smart city lifecycle processes, such as conceptualization, planning, development and maintenance.

As was shown before, to cope with the complexity of urban issues and to make cities smart and sustainable, different ICTs have been used. But since a lot of information that has to be managed is linked to location or is geo-referenced, GISs have provided solutions when it comes to urban planning, transportation modelling, risk management, demographics, etc. As is the case with the different ICTs, GISs have undergone rapid changes and development in the last decades and gained on popularity (see figure 3.4). In fact, GISs can be considered as an essential part of a wider scope of ICTs in urban management (Tao, 2013). In many cities it has become a basic tool to assess spatial issues and finding solutions. Some general applications that have evolved from the use of GISs in smart cities are urban modelling, site selection and land acquisition, environmental and legal compliance, design and visualization, construction and project management, operations and reporting, to name a few (Esri, 2018). Section 3.6 will further elaborate on specific GIS and geospatial applications for smart cities.

Figure 3.4: Geospatial literacy growth in modern versions of cities.



Source: Tao, 2013

Spatial data/information types

Geospatial data comes in several data formats (e.g. Esri shapefiles, (geo)json, kml, dwg, etc.) and can be very large in file sizes and size of (geo-)databases. Data that are usually available compromise digital terrain and elevation models (DTM & DEM), point clouds (LAS), aerial/satellite images, 2D/3D geometries, triangulated irregular networks (TIN), geography markup language (GML), and metadata, to name a few. A way to organize this data is through the use of a Spatial Data Infrastructure (SDI). Such an infrastructure can help with creating 3D city models by means of organizing 3D geospatial data, by generating 3D models of city objects, and by visualizing these 3D city models (Guney, 2016).

The next section describes Spatial Data Infrastructures (SDIs) in more detail and the relation with GISs.

3.3. Spatial Data Infrastructures

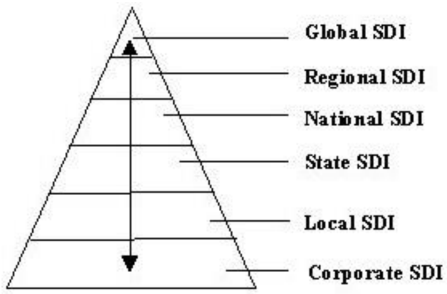
Now that the smart city concept is explained and the short-lived relationship with GIS is described, a more detailed discussion about Spatial Data Infrastructures (SDIs) can be held. A GIS can be part of an SDI, but it is not the entire SDI. An SDI is the whole framework and network of geospatial data and involves everything from standards to data to databases to software. This section outlines what an SDI exactly is, which different examples exist, how they are used and how an SDI can serve smart cities.

.

Definition

The term Spatial Data Infrastructure was presumably coined in 1993 by the United States National Research Council to describe a framework of technologies, policies and institutional arrangements. Together these facilitate the creation, exchange and use of geospatial data and related information resources across an information-sharing community (Esri, 2010). Doing so, this framework can be applied on different scales. For example, it can enable the sharing of geospatial data within just one specific organization, or it can be implemented on a larger scale, for instance on a local, national, regional or global level. An example of a local SDI is Maps Amsterdam (Gemeente Amsterdam, 2017). An example of a national SDI is the Dutch Publieke Dienstverlening Op De Kaart (PDOK, 2017). An example of a regional SDI is the Infrastructure for Spatial Information in the European Community (INSPIRE).

Figure 3.5: SDI hierarchy of SDIs at different levels of jurisdictions.

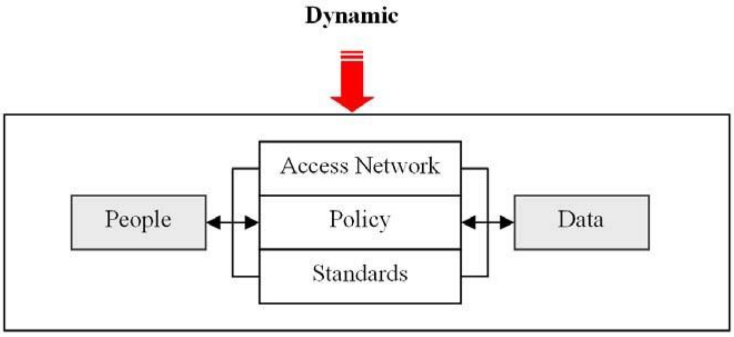


Source: Rajabifard & Williamson, 2001

SDI components

SDIs consist of certain components that make up the nature of the concept (figure 3.5). When put together in a model these faintly resemble smart city architectural models. Although the latter is more focused on technical implementations, the SDI model is more of a conceptual model.

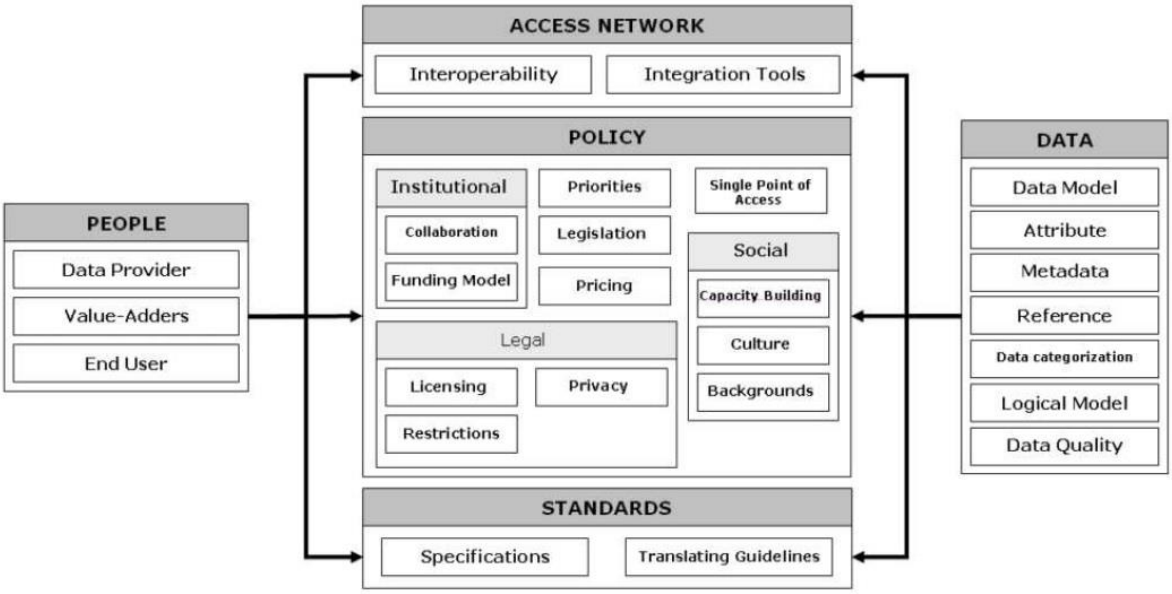
Figure 3.6: SDI nature and components.



Source: Crompvoets et al., 2008, p. 13.

When looking into more detail of what these concepts consist of, one can distinguish the technological components related to these concepts (figure 3.6).

Figure 3.7: SDI and its technological components

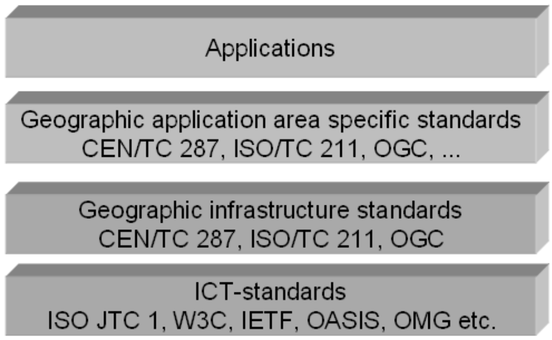


Source: Murakami et al., 2011, p.1

SDI standards

SDIs are embedded in ICTs with spatial data as focus. Hence, it is not so strange that there are also standards in support of SDIs (figure 3.8).

Figure 3.8: The stack of standards in support of SDIs



Source: Bregt, 2016

As can be derived from this figure, ICT standards coming from different sources are at the basis of any SDI. Next, there are standards specifically designed for geo-information related concepts and technologies. Organizations like ISO, CEN and OGC (in The Netherlands Geonovum on a smaller scale) have a key role in formulating them. They can be divided in three main categories:

- Metadata
- Spatial data reference models
- Services

These standards can also be referred to as geo-standards. The next section (3.4.) describes them.

Different versions

As is common with GIS technologies, there are multiple versions of such an SDI. Some of which are still in a conceptual phase, and some already being implemented. Also, there is a variety in end usage and a difference between the use of 2D and 3D geoinformation. An SDI can also be implemented on an even smaller scale than local, namely on district level. An example of this, is the Smart District Data Infrastructure (SDDI). Although this is currently mainly a conceptual framework, it proposes a fully integrated platform for combining smart city approaches and technologies with 3D geoinformation and a 3D city model (Virtual District Model). This holistic SDDI framework is discussed in the next paragraph.

SDDI explained

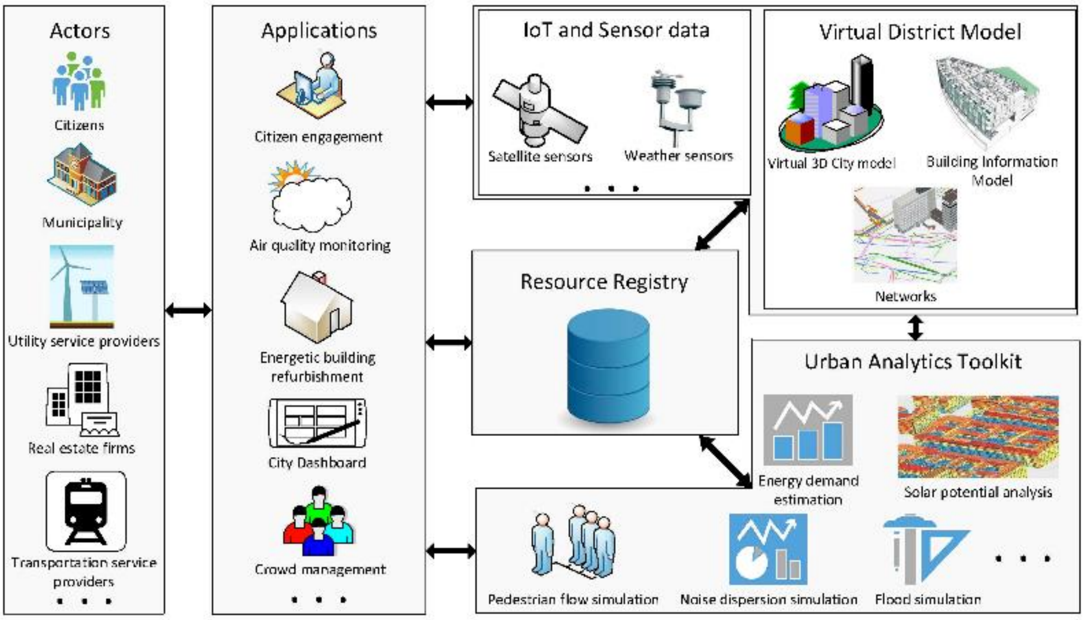
The SDDI is a specific version of an SDI. In this paragraph it is explained what the different components are and how it sets itself apart from other approaches.

The SDDI is based on a modular structure and on open (data) standards and combines different data sources and types in a non-commercial or non-proprietary way, making it extensible to other platforms and/or software. It defines an organizational and technical framework consisting of several entities such as actors, applications, sensors, analytic tools, and a city model

(TUM, 2017). Actors are defined as citizens and local government employees, but also as public transport services, utility service providers, real estate firms, and other parties that collaborate in a project. These can also be referred to as stakeholders. Sensors can contain weather stations, energy meters, water meters, video cameras, and traffic sensors. Analytical tools can be software components that estimate spatial phenomena and energy usage and production for example.

The SDDI framework differs from other SDIs within the field of smart cities in the fact that all information, sensors and applications are located within a semantic 3d city model which is based on the international standard CityGML (City Geography Markup Language). Next to serving for attractive visualizations it can be regarded as an information hub and as foundation for simulations and spatial analyses. For example, the energy demands of buildings can be put in relation to their physical conditions and their socio-economic key performance indicators (KPIs). Using this concept, urban redevelopment projects can assess the impact of different plans or scenarios on thematic fields such as environment, energy, mobility, and social affairs.

Figure 3.9: Smart District Data Infrastructure conceptual framework



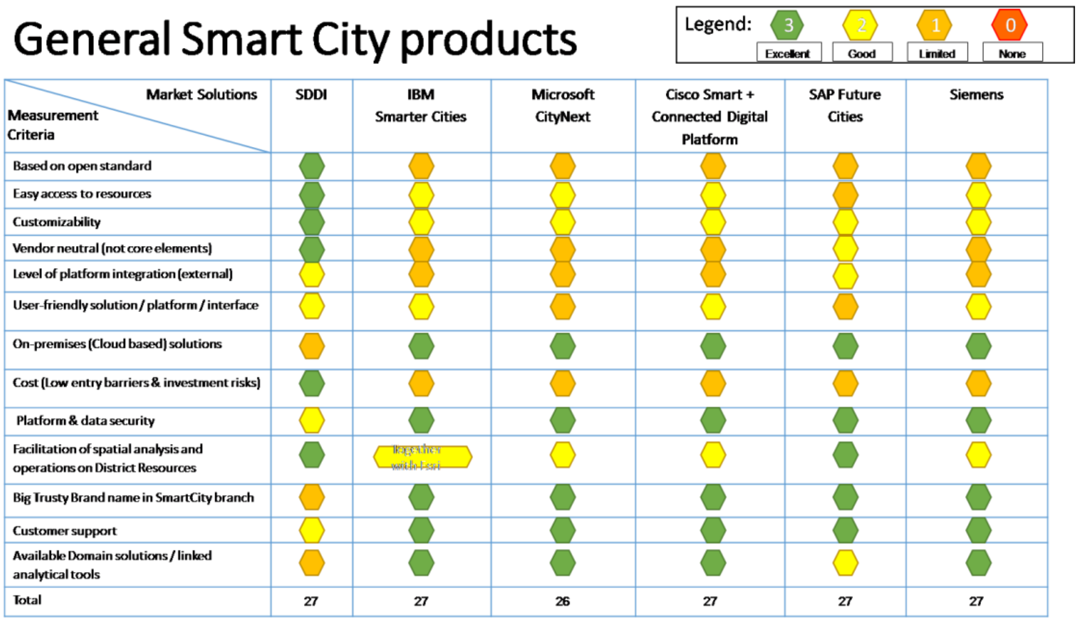
Source: Technical University Munich, 2017.

When looking at the aspects of smart city development, such as the approaches, technologies and trends, standards, data and architecture as described in chapter 2, the SDDI framework incorporates all of these aspects.

SDDI compared

Concluding in this section is an overview of general smart city products that has been made, in part, by the Technical University of Munich. These products have been assessed on several measurement criteria and a total score is provided. The other products are commercially available market solutions, which score remarkably less on the use of open standards, accessibility of resources, customizability and cost. But on the other hand, they score better when it comes to platform and data security and customer support for instance. When the total scores are combined the smart city products do not differ much from each other.

Figure 3.10: SDDI compared



Source: TUM, 2017

SDI assessment.

Other ways of assessing SDIs have also been defined. There are actually nine approaches to assess SDIs according to Crompvoets et al. (2008). These include SDI-Readiness, clearinghouse suitability, INSPIRE State of Play, organizational, evaluation areas for SDI, performance-based management, metaphor organization, legal and effectiveness from a user's perspective (figure 4.5). These approaches each treat SDIs from various viewpoints and have different objectives. They also implement multiple assessment methods such as surveys, case studies, personal interviews with key people, and document studies. The goal of these various approaches is to generate completer and more realistic, and less biased results.

Figure 3.11: Assessment approaches proposed for the multi-view assessment framework

Assessment approach	Goal Description	Method	Applicability	Assessment purpose class
SDI-Readiness	To assess if the country is ready to embrace the SDI development	Survey	Applicable	Developmental Knowledge
Cadastral	To measure five evaluation areas of LAS	Survey	Needs improvement	Knowledge Accountability
Organisational	To measure the SDI development from the institutional perspective	Case study	Applicable	Developmental
Performance-Based	To measure the SDI's effectiveness, efficiency and reliability	Not available	Needs improvement	Accountability
Clearinghouse Suitability	To measure the development and impact of SDI clearinghouses worldwide	Survey, key informants	Applicable	Developmental Knowledge
State of Play	To measure the status and development of SDIs	Document study, survey, key informants	Applicable	Developmental Accountability
User's perspective	To measure the SDI's effectiveness from the user's perspective	Case study	Needs development	Accountability, Knowledge
Metaphorical	To analyse organisational and management aspects of the SDI	Literature review	Needs development	Knowledge
Legal	To measure compliance, coherence and quality of the SDI legal framework	Case studies	Needs improvement	Knowledge

Source: Crompvoets et al, 2008.

When in the continuation of the SSD project the SDDI might be implemented, one of these assessment approaches might be of use to research it. If one of these approaches would be used to assess the SDDI it would merely be a theoretical analysis. This 'what if…' approach might not be suitable.

The next section discusses geo-standards.

3.4. Geo-Standards

Geo-standards make it possible to exchange data and information with a geographical component in a digital and unambiguous way. This information can then be (re-)used in several software programs and with several end goals. As can be read in the previous section, geo-standards serve as the backbone of a Spatial Data Infrastructure.

Geo-standards can be subdivided into two groups. The first group contains standards for the description of geo-information, including information models and standards for metadata, exchange and coordinate reference systems. With these standards the geo-information (data) itself is described. The second group contains standards for services, including those for serving vector, raster and sensor data. These standards describe how the data is served.

In the Netherlands, Geonovum is the main organization that takes care of and manages the set of geo-standards that is relevant for the Netherlands. This set contains the Base model Geo-information (NEN3610) which can be regarded as the 'mother' of many information models in which dataset semantics are captured. Next to that there are standards for the exchange of datasets (GML), the unlocking of datasets (WMS, WFS), and making them findable through metadata profiles (ISO19115) and for services (ISO19119).

Another example that can be found is 3D geo-standards. Over the years, 3D data has served many purposes and hence several 3D standards have emerged. A comparison between them can be found in figure 3.8. Different standards have been weighted on a multiplicity of criteria.

Figure 3.12: Comparison of 3D standards in CAD and GIS domains

Standard/Criterion	DXF	SHP	VRML	X3D	KML	Collada	IFC	CityGML	3D PDF
Geometry	++	+	++	++	+	++	++	+	++
Topology	-	-	0	0	-	+	+	+	-
Texture	-	-	++	++	0	++	-	+	+
LOD	-	-	+	+	-	-	-	+	-
Objects	0	+	+	+	-	-	+	+	+
Semantic	+	+	0	0	0	0	++	++	+
Attributes	-	+	0	0	0	-	+	+	+
XML based	-	-	-	+	-	-	+	+	-
Web	-	-	+	++	++	+	-	+	0
Georef.	+	+	-	+	+	-	-	+	+
Acceptance	++	++	++	0	++	+	0	+	++

- not supported; 0 basic; + supported; ++ extended support

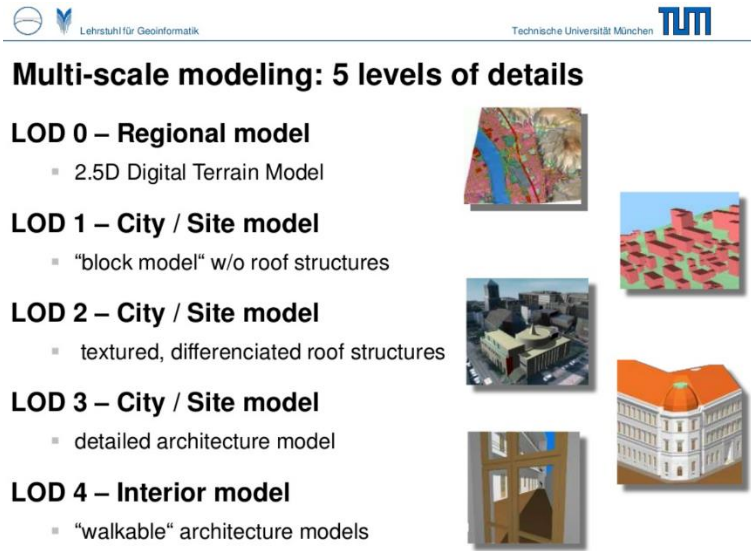
Source: Stoter et al. (2011)

Although other 3D standards have their own benefits, it shows that the CityGML standard scores best overall. One of the most used formats to virtually represent a city is CityGML. The next paragraph describes this format.

CityGML

This paragraph explains the benefits and shortcomings of the international CityGML standard. The CityGML standard can be applied to many research, policy and planning areas. Among them are: disaster management, urban planning, navigation, environmental simulations etc. CityGML represents four different aspects of virtual 3D city models, i.e. (1) semantics, (2) geometry, (3) topology, and (4) appearance. Next to that, it can hold five discrete scales of representation which are named the Levels-Of-Detail (LOD, see figure 3.9).

Figure 3.13: CityGML levels of detail.



Source: TUM, 2015

CityGML is regarded as the most promising 3D standard. Hence, it is established as an international OGC open-source standard developed independently, instead of as a *de facto* industry standard. CityGML provides for semantics (which is more than just visualization), georeferencing and Web use, whereas other graphical or geometric models are limited to visualization purposes only (Brink et al. 2013). It can be reused so that possible costs are reduced.

CityGML is also based on GML3 and therefore it perfectly combines with other OGC standards such as the Web Feature Service (WFS), the Catalog Service (CS-W), the Web Coordinate Transformation Service (WCTS), and the Web Processing Service (WPS). When aiming to produce 3D visualizations, CityGML can be considered as a format from which other 3D graphic formats can be derived.

Shortcomings CityGML

During the development of CityGML and when trying to introduce it as an industry standard, discussions were held about the possible shortcomings of CityGML. Arguments against it were that the standard is generic, it doesn't know object definition, and it doesn't support complex geometries as is the case in the CAD domain (Geonovum, 2011). Other problems are the focus on ground objects, uncertainty on when to apply which Level-Of-Detail (LOD), the lack of relations between LOD's and the missing support for geometrical validation. Next to that there's a limited support for CityGML in commercial GIS systems, although this is being improved.

3.5. Supporting Techniques

This section describes the supporting techniques that can be put to use when incorporating spatial information in smart cities. In chapter 2 an overview was given of the technologies and trends that are leading in smart city development. These are networking and communications, Internet of Things, open data, big data, cloud computing, citizen engagement and digital cities (3D models). These technologies are still quite general and it can be argued that they do not necessarily require spatial information. The argument of this thesis however, is that smart cities possess spatial intelligence and that GISs play a key role in providing a theoretical framework and practical procedures for data acquisition, processing, analysis and representation. The techniques described here are suited for these procedures.

Gruen (2013) has provided some of the geospatial techniques that can be used in smart city development. These are automatic or semi-automated generation of Digital Surface Models (DSM) from satellite, aerial and terrestrial images and/or LiDAR data, further development of the semi-automated techniques onto a higher level of automation, integrated automated and semi-automated processing of laser-scan point clouds and images, both from aerial and from terrestrial platforms, streamlining the processing pipeline for UAV image data projects, exploring the various applications of UAV-based thermal imaging, set-up of GIS with 3D/4D capabilities, change detection and updating of databases, combination of real and synthetic (e.g. planned) objects (reality-based and generic modelling) – see CC-Modeller and City Engine, handling of dynamic and semantic aspects of city modelling and simulation (which leads to 4D city models), LBS system investigations (PDAs, mobiles), and establishment of a powerful visualization and interaction platform.

Possible future techniques or techniques that are existing but have to developed are location cloud, remote sensing cloud, integration of video and GIS, integration of spaceborne, airborne and terrestrial sensors and GIS, indoor and underground navigation, ubiquitous sensing via smartphones, and spatio-temporal data mining (Li et al., 2013).

3.6. Geospatial Applications for Smart Cities

This section describes geospatial applications. In the previous chapter, smart city applications have been described. There it was made clear that an application can be anything that uses data and data services to provide a solution or insight in current problems and development. Typically, it's a computer program or software that can help users perform certain tasks, functions or activities for the user's benefit.

The difference with geospatial or GIS applications is that in these applications data and data services are related to location. Hence, the tasks, functions and activities also have a geospatial component in them. There is a wide variety of GIS applications and uses nowadays, as GIS development has taken a leap over the recent decades, as could have been read in section 3.2. In fact, over a 1000 GIS applications can be distinguished from over 50 industries (GISGeography, 2018). These industries range from agriculture to archaeology to astronomy to telecommunications to weather and so forth. A major industry in this selection is municipality and urban planning GIS applications. Smart cities are also named as a specific GIS application, with the goal to integrate urban development visions with GIS such as smart urban planning, smart utilities, smart transportation, smart public works and citizen engagement.

GIS applications specific for smart cities in general constitute the following themes: site selection and land acquisition, environmental/legal compliance, planning, design and visualization, construction and project management, sales and marketing, facility management, and operations and reporting (Esri, 2018). GIS applications for smart cities differ from other applications as it offers an IT framework which may integrate all the stakeholders and smart city processes. Oftentimes these applications request or aim to provide 3D geodata and information. The next section goes into more detail about 3D geo-information.

3D geoinformation

This section discusses three-dimensional (3D) geographic information and outlining the current transition from two-dimensional (2D) geographic information systems to 3D GISs. Next, the details of 3D data are handled, the technical functionalities it has and the possible applications of 3D city models and 3D standards that have emerged (in particular CityGML).

An increasing number of cities worldwide are transitioning from using 2D GISs to 3D (web) GISs (Guney, 2016). Recent examples can be found in Berlin, Rotterdam etc. (see next section) This is due to rapid advancing technologies, the need of the public, and the added value that 3D GIS can have. Next to these government entities, commercial companies such as Google, Apple, Here, TomTom, SAP are undergoing the same transition. A third community is also building 3D city models through the use of Volunteered Geographic Data/Information and open-source programs such as Open Street Map and CityGML. City governments are urged to build 3D information systems for applications such as Land Administration Systems and 3D spatial planning to assist in representing legal space in the city for land management (Indrajit et al., 2018).

It is important to understand what 3D (geo-)data is and how it differs from 2D or 2.5D data. This paragraph gives a short explanation and discusses the added value of 3D GIS data over 2D or 2.5D data. 3D GIS data incorporates an extra dimension in the form of a z-value. This is an addition to the 2D x- and y-values and thus can store and display more information. Often, z-values represent height or elevation values such as the height above sea level or geological depth. But they can be used to store other information as well, such chemical concentrations, the suitability of a location, or other values for many different purposes (Esri, 2017). For 3D GIS purposes however, the z-value is most often used to store elevation or height data. In general, two types of 3D GIS data can be distinguished: feature data and surface data.

Once 3D GIS data is available or acquired, it can serve for analysis, among other purposes. Some specific functionalities that it has are based on 2D functionalities. For instance, one can query a 3D GIS database with functions such as *3D Distance, 3D Buffer, 3D Density* etc.

3D city model applications

In this paragraph, an overview and comparison of 3D city model applications that are currently in the market is given. Possible uses or applications of a 3D city model can be: pedestrian flow simulation, air pollution modeling, water network modeling (and runoff), solar energy potential analysis, shadow impact analysis, and zoning regulations, to name a few. Biljecki (2017) identified 29 use cases of 3D city models. These are: (1) Estimation of solar exposure, (2) Energy demand estimation, (3) Aiding positioning, (4) Determination of floorspace, (5) Classifying building types, (6) Geo-visualization and visualization enhancement, (7) Visualization for navigation, (8) Visualization for communication of urban information to citizenry, (9) Visibility analysis, (10) Estimation of shadows cast by urban features, (11) Estimation of the propagation of noise in an urban environment, (12) 3D cadaster, (13) Urban planning, (14) Reconstruction of sunlight direction, (15) Understanding synthetic aperture radar images, (16) Facility management, (17) Automatic scaffold assembly, (18) Emergency response, (19) Lighting simulations, (20) Radio-wave propagation, (21) Computational fluid dynamics, (22) Estimating the population in an area, (23) Routing, (24) Forecasting seismic damage, (25) Flood simulations, (26) Change detection, (27) Volumetric-based density studies, (28) Forest management, (29) Archaeology.

Other applications are for instance the use of 3D city model for 'geodesign' (Steinitz, 2012). Geodesign is a set of concepts and methods to get all stakeholders and different professions involved in order to collaboratively design and realize the optimal solution for spatial challenges in the built and natural environments, utilizing all available techniques and data in an integrated process. In practice it is supposed to extend GISs so that users can create new environments and modify geodata, in addition to analyzing existing environments. In geodesign, virtual 3D models of the environment (e.g., landscape models or urban models) can facilitate exploration and presentation as well as analysis and simulation. Esri's new product ArcGIS Urban makes use of the geodesign and 3D city model combination.

Another often named application is the concept of having a 'digital twin'. A digital twin is a digital replica of a living or non-living physical entity (El Saddik, 2018). It refers to a digital replica of physical assets (physical twin), processes, people, places, systems and devices that can be used for various purposes. Hence, the term can be used in many other concepts besides smart cities. In the context of smart cities however, a digital twin is a digital model of the city's physical assets, which collects information via sensors, drones, IoT, citizens, etc. and applies advanced analytics, machine-learning and artificial intelligence (AI) to gain real-time insight about the physical asset's performance, operation or profitability (Weekes, S., 2019).

A possible application that is emerging and is currently being researched is the integration of Building Information Models (BIM) into GISs (e.g. Yamamura, 2016). The buildings sector is working a lot with 3D models, however, these are not always directly exchangeable and interoperable with GIS systems. As GISs and 3D web applications become more powerful, this could provide a powerful solution for the detailed 3D modelling of city environments.

Sensor networks

The concept of a smart city involves the observing the state of their environment and the activities that are taking place in order to improve overall services. Sensors in the city are thus vital to understanding and monitoring the state of a city and to reacting to its needs. These sensors can be deployed in city-wide sensor networks. There is a variety of sensors and sensor networks that are designed to measure and quantify environmental conditions for example, such as the weather, air quality, noise pollution, aerosol content, soil moisture, etc. Sensors and sensor networks now form the basis of most environmental monitoring (e.g. through remote sensing and in situ sensing) (Sagl et al., 2015). But from their original purpose of usage in environmental applications, sensors and sensor technology have spread to other purposes such as human health, sport activities, transport, mobility, etc. For the sake of overview, Sagl et al. (2015) categorized the types of sensors into technical sensors and human sensors (see figure 3.14).

Figure 3.14: Types of sensors

Term	Related Terms	Characteristic Context Parameters, and Application Fields
	Technical Sensors—*in Situ* Sensors	
Environmental sensors	Environmental monitoring, urban sensing	Meteorology and weather [24,25] Air pollution/quality monitoring [26–31] Heat island detection [28,32,33] Flood monitoring [34,35] Nuclear radiation safety [36–39]
Mobile sensors	Wearable ambient sensors, mobile sensor web	Ubiquitous measurements, e.g., through bike-mounted sensors [40–43] Disaster management [37,44–47] Embedded mobile sensor web, application-independent [48–50]
Pervasive sensing	Ubiquitous sensing, socially aware computing	Smart and aware environments and homes and ambient/active assisted living [51–58] Pervasive healthcare [59–61] RFID-based location and tracking [53,62,63] Socially aware computing [14,18,64,65]
	Technical Sensors—Remote Sensors	
Remote sensors	Remote technical sensors and remote sensing systems, from satellite-based to terrestrial	"Classic" airborne and spaceborne optical systems [66–70] New developments: high resolution, hyperspectral, LiDAR, UAV [67–74] Thermal [75–77] Atmosphere/Aerosols [78–81]
	Human Sensors	
People as sensors	Citizens as sensors, citizen sensing, human sensing, human sensors, humans as sensors, physiological sensors, wearable body sensors, participatory sensing, Volunteered Geographic Information (VGI)	Flood monitoring [35,82,83] Generic participatory sensing and sensing platforms (for smart cities) [84–95] Physiological parameters such as pulse, oxygen saturation, stress levels [96–101] Disaster and incident management [23,83,102] Noise mapping [103–107] VGI in general and in some of the above mentioned examples (including postings in social media regarding public health, air quality *etc.*) [108–118]
Collective sensing	Mobile phone sensing, crowd sensing, social sensing, online sensing, social media	Disaster and incident management [115,119–122] Mobility patterns and transportation [22,105,123–130] Socio-physical context estimation [97,105,131–133] Tourism [124,134,135] Epidemiology and disease detection [136–139]

Source: Sagl et al. (2015)

Nowadays, there are hundreds of millions of Internet-connected sensors in, on and around planet Earth. Standardization is thus essential for communicating (location) information about sensors and sensed phenomena. A framework that provides standards for these is the OGC's Sensor Web Enablement (SWE) framework. This provides a suite of standards that make it easier to integrate sensor information into geospatial applications that support the development of smart cities.

As one can distinguish, there is a wide variety of applications possible when using 3D geo-information and models constructed from this information. The next section provides a few examples of 3D city models in a smart city context.

3.7. 3D Smart City Models: Examples

This section provides a few examples of 3D city models in a smart city context. It is reviewed what functionalities they have, what (geo-)data and information they include and which applications they serve. The focus here is on non-commercial models developed for governmental purposes. Commercial products as developed by companies such as Esri, Hexagon, Bentley etc. are not taken into account. Also, the 3D city models reviewed here are freely available online through a web browser and are not standalone, local models running on a game engine for instance.

By providing these examples, the VDM prototype developed in this thesis can then be compared to the common characteristics of these models (see section 6.4.).

Rotterdam

One of the most well-known and prime examples of 3D city models in smart city context in The Netherlands is developed by the municipality of Rotterdam, together with the companies FutureInsight and VirtualCitySystems, in a Cesium web environment. Rotterdam 3D is a three-dimensional representation of the municipality based on a number of 'basisregistraties' (administrative geoinformation of housing and topography, etc.), height data, maintenance data and photo material. It includes buildings, trees, lamppost, cables and pipes (underground). It has functionalities such as making measurements (distances), shadow casting, drawing and a download/export option with the option to select a particular object or a larger area which makes it able to download a 3D model in various data formats so that it can be used in other software. Rotterdam 3D is regarded as a digital twin and also includes BIM integration and thematic information. In terms of usefulness, city managers and developers can use the model and the (topographical) data to visualize environmental plans and future scenarios. It is also easier for them and residents to gain insight into where, for example, underground containers can best stand. With the model, city management has a lot of information about the physical city. From compaction to asset management and from circular to climate adaptation, 3D information provides insights that help the city. For example, with the 3D model one can make analyzes of, for example, shadow, sound, sight lines and sun potential of roofs.

Gothenburg

Another example is an online 3D city model by the City of Gothenburg, Sweden, named 'Min Stad'. Min Stad is a place to exchange ideas about land-use planning in Gothenburg. Citizens can create suggestions in an interactive 3D-version of the city and share it with other people. Various categories are provided such as culture, recreation, cycling, socializing, etc. It is coined a 'digital bulletin board' where the city's government hopes a lively and open debate takes place regarding the city's civic potential. Everything submitted in to Min Stad will be used as inspiration for city planning work by the City of Gothenburg, aimed to help the city build a green and sustainable city. The suggestions that citizens can create are managed by people working in the department of city planning and are used to aid in urban planning work. It is developed with the help of CityPlanner. CityPlanner is a web platform that hosts data and applications with large 3D city models built using mesh photorealistic details, similar to Google Earth. It runs in a web browser by using HTML5 and WebGL javascript library. Agency9 hosts the 3D model and all work is done within a browser. CityPlanner offers limited analysis capability. Except for height analysis and shadow studies, other analysis is completed before bringing the model into CityPlanner scene. The mesh model that CityPlanner employs is highly realistic. But, because the model is not precise, GIS users may not like it. The mesh model can also be difficult to update. In a rapidly changing city or district, a new mesh model would have to be made every second year. Planners who do not need the precision of GIS typically find CityPlanner to be a fine tool.

Berlin

The Berlin 3D City Model represents one of the world's largest municipal city models and is one the earliest models available (since 2003, see Dollner et al., 2006). It contains 560,000 fully textured building models in Level of Detail 2 (LoD2) and more than 200 detailed models in LoD3/4. The city model is the basis of the Berlin Economic Atlas and the Solar Atlas. The model provides a unique database for research and development of processes and IT solutions for the visualization and analysis of 3D spatial models. Specifically, the model is used in the field of ‘Urban Analytics’ as the basis for communication of complex spatial data and processes. It is freely available to the public as open data in CityGML format. The open data is provided via a web-based service portal through which users can select and download individual building models in a variety of 3D data formats. In addition, the Berlin CityGML model has been exported to a tiled KML/glTF dataset using 3DCityDB and can be explored using the 3DCityDB-Web-Map-Client based on Cesium.

New York

Another interesting example of an online 3D city model application is a semantic 3D city model of New York City. It has been created based on open datasets available in the NYC Open Data Portal. It comprises not only buildings but also land parcels, roads, parks, the digital terrain model, and water bodies – all with 3D geometries. It is the first publicly available big 3D city model of a large city in the USA which is based on official governmental data. The resulting CityGML / KML / COLLADA / glTF datasets are available for download as open data. Next to that a 3D web-based visualization of the entire city model is provided. Data includes buildings, land parcels, roads, parks, the digital terrain model, and water bodies. The web map client contains all street space objects as well as all building objects of New York City in LoD2. More than 1'000'000 building objects and more than 500'000 street space objects were generated entirely from open data. Multiple thematic layers, each enriched with a variety of semantic information, can be selected individually. Extended analysis can be performed with the Pro version of the web map client.

These analyses are potentially useful for (urban) land use management, city asset management, or city planning. The city model presented contains a huge variety of semantic information such as street names, number of driving lanes, street area in m2 or information on road surface conditions. These attributes can be queried in different combinations and thus be used for gaining additional information.

Common characteristics

After briefly reviewing these four examples of 3D city models in a smart city context a few common characteristics can be distinguished. They all provide free-to-use online web interfaces that visualize 3D city data. These 3D visualizations can in all cases be used interactively. Some applications show great semantic and thematic information, and not only building information but also other 3D geometries such as roads, DTM's, water bodies, etc. The data that has been used or is provided in these examples is oftentimes open data. Citizens can be engaged actively as is shown in the Gothenburg example.

However, what is also discovered by reviewing these examples, is that most 3D models have been developed in cooperation with commercial companies and are part of (research) projects spanning multiple years. This is a characteristic that must not be overlooked. It shows the scale of developing such applications.

For the sake of overview and comparison later onwards, the characteristics are listed here:

- Free, online access
- Open data based
- Specific functionalities
- Semantic and thematic information
- Interactivity
- Citizen engagement
- Large projects

This section provided some examples of 3D city models being used in a smart city context. However, there are many other similar applications, the brief review done here is far from complete but serves as basis for comparison with the prototype developed for this thesis. Section 6.4. covers this comparison. The next sections provide the discussion and conclusion of this chapter.

3.8. Discussion

Although there is no straightforward definition of a smart city, and it still remains a fuzzy concept (Witte & Geertman, 2017), as was discussed in chapter 2, the key domains in which cities can develop their smartness and which they can use to build more sustainable, resilient and responsive cities are economy, people, governance, mobility, environment and living, as pointed out by Giffinger et al. (2007). In almost all these areas, the role of spatial information is present and geospatial components combined with other and new technologies can be used as a framework to support actions in these domains. Relevant data can for instance be visualized, organized, analyzed and interpreted by using interactive web maps. These web maps, as prime example of a geospatial application in smart cities, can be used to enhance stakeholder collaboration (governments, institutions, companies, citizens). They provide insight for discussing, interacting and decision-making.

Some other examples that support the use geospatial technologies in building smarter cities are (1) that it can increase efficiency in public services by improving stakeholder collaboration, (2) maps and 3D models are a good way to inform and engage citizens, (3) it can assist in emergency response, (4) digital maps can bring communities together, (5) applications based on spatial information can improve commute and mobility. These are just some of the examples that can be used to argue for the use of geospatial technologies in smart cities.

A growing topic and technology in relation to this is the use of 3D geo-information. From the literature review it is shown that this kind of information and data is particularly useful for building smarter cities as it may provide many sorts of applications.

Criticism on the role of spatial information in smart city development might be that spatial data might 'big' very quickly. Alongside location-specific information, spatial data models often need or aim to incorporate 3D information, residential records, citizen knowledge, historical data etc. (Wammes, 2015).

3.9. Conclusion

To conclude this chapter and to give answer to the question how available geospatial technology and data can contribute to building smarter cities, an argument was made how organizing and making use of spatial information is a crucial step, if not the first step in smart city development. GISs making part of larger SDIs can serve as smart city managing platforms or IT frameworks.

Data used in smart cities as such can generate information that is needed to acquire understanding and knowledge about a city's smartness. Geodata however, i.e. data with a geographical component, can be used to generate information which is relevant (or even vital) for decision-making processes. Almost all of these processes involve information acquired from geodata (hence it can be called geo-information) such as location and demographic information. Geo-information can be considered special for economic, legal and technical reasons (see Donker, 2016 for an extensive review). For technical reasons because geo-information is multi-dimensional, voluminous, dynamic, and can be represented at multiple scales. This complexity of geodata requires system components that are specific for this kind of data, such as specialized hardware and software, tools for analysis, and people's skill-set to collect, process, and use geodata and information.

A smart city information system extended with or built on these geospatial components may be the ideal system for all stakeholders. A virtual 3D model of a city can be the basis for both sectoral and integral applications and can host different input technologies. A digital city is a fundamental framework for a smart city. Data from smart sensor networks can be updated and published under the infrastructure framework of a digital city, resulting in easier interaction between humans and machines and provide useful information (Li et al., 2013).

The difference with smart city information systems and frameworks that do not consider a spatial component is that when using spatial information, data can be geo-referenced, and data can be handled in an object-oriented way. Organizing smart city data in a spatial model provides great benefits when it comes to data visualization. It can show complex urban information in a simple and direct way, hence establishing interaction between users and data. It also provides all the strength that GISs and SDIs can provide, as is discussed in their describing sections.

Comparison smart city information system requirements

In the previous chapter the requirements for a smart city information system have been concluded. This paragraph aims to compare these requirements with geo-information and GIS tools and how they can be met by using geospatial technology.

- *Facilitating the organization of the data, applications, services, sensors of a city in a common framework and technological ecosystem (clear and stable architecture)*

The previous sections have demonstrated what abilities and possibilities the use of geospatial technology and related concepts have. To organize the data, applications, services, sensors of a city in a common framework one can make use of a Spatial Data Infrastructure (SDI). Different versions of these exist, in particular the SDDI, but in general this concept provided a framework and technological ecosystem.

- *Low entry barriers / low investment risks / high flexibility*
  - *low operation costs (open source and flexible software)*
  - *no migration costs, because existing systems and platforms are interfaced*
  - *easily and incrementally extendible: datasets, applications, services, and tools can be added and used anytime and by third parties (open standards and open access)*

The requirement of a smart city information system to have low entry barriers/investment risks/high flexibility can be met by using open source software and open (geo-)standards. The initial costs of existing systems might have been high and might be great to maintain, but they do not necessarily have to be replaced. An additional (SDI) layer makes sure these systems are connected.

- *Facilitation of easy and user-friendly access to city resources (dashboards, maps and other communication tools*
  - *to the customer and its partners; also to the public (practical use and user experience)* (*webportal for communication, citizen engagement)*
  - *accessibility to (geo-)data and (geo-)information* (*online data catalogue with download option)*
  - *Providing an intuitive 3D geographic view onto the city resources* (*3D webviewer*)
  - *User clients incl. 3D visualization run on any platform, operating system, and browser without extra installations; incl. mobile systems* (*domain application layer*)

To facilitate easy and user-friendly access to city resources GIS software and tools and data visualization (maps, 3D models, etc.) can play a great role to enhance accessibility to smart city (geo-)data and (geo-)information. Extended by other system components such as services (e.g. WMS/WFS), web interfaces and mobile applications based on geodata this requirement can be met. However, users must have some understanding of what is visualized or represented, a certain 'map literacy' is required.

- *Support of planning and decision making*
    - *Visualization of newly planned buildings in the geographic context using a 3D city model* (*digital twin*)
    - *Facilitation of urban simulations like solar potential analysis, building energy demand estimations*

The greatest value of using geospatial information and technology lies in the support of planning and decision-making. Especially 3D digital models have the ability to support a great number of domain specific applications. It makes it easier for stakeholders to grasp the meaning of new urban development plans. Also, more detailed and realistic simulations can be held which can contribute to future policy and decision-making.

Chapter 2 and 3 have aimed to answer the research questions '*What is the ideal smart city information system and what are its requirements?*' and '*How can available geospatial technology and data contribute to building smarter cities?*' The next research question '*What is needed to build a prototype smart city information model?*' will be answered by using a case study. The next chapters will dive into this.

4. Case Study: Smart Sustainable Districts Project Utrecht

This thesis emerges from a real-life project and researches the role of geospatial technologies in smart city development. It aims to do so by creating and evaluating a prototype information system. The application is a Virtual District Model (VDM), developed with CityGML, for a district in Utrecht, The Netherlands. The VDM is part of a Smart District Data Infrastructure (SDDI), a smart city information system, developed by the Technical University of Munich (TUM) and a first step towards realizing an SDDI. This SDDI is an adaptation of the Spatial Data Infrastructure (SDI) concept. SDDI takes the 'digital city' technique (cq. 3D virtual city model) as starting point in which all data and information can be stored in an object-oriented way (Li et al., 2013). The next paragraphs explain the project's context, how the need of such an application emerged and the SDDI in more detail.

4.1. Context

In the light of the current developments in sustainability, the municipality of Utrecht, together with the Jaarbeurs (an exhibition and conference center), strives to design a 'Smart Sustainable District' (SSD) in the station area, called Utrecht Centre West. The Utrecht Central Station area is part of one of the major transformation projects in the Netherlands.

Within this project, several partners and stakeholders are involved (figure 4.1). These stakeholders have at some point in their process expressed their interest in an information system to support decision-making and have defined certain user requirements. One of these tools is a three-dimensional (3D) city model. All over the world more and more cities are adopting 3D city models as they provide added value and utilities over two-dimensional (2D) geo-datasets.

Figure 4.1: Overview of Smart Sustainable District stakeholders.

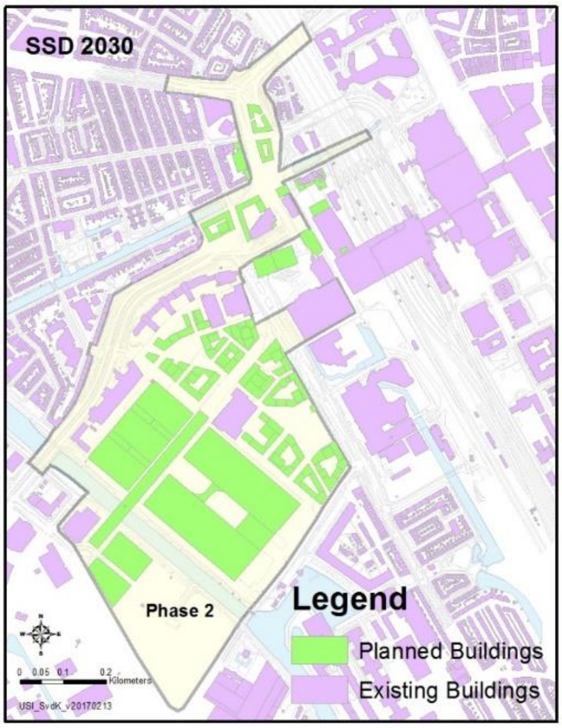
Source: SSD Utrecht, 2017.

4.2. About the district Utrecht Centre West

The municipality of Utrecht is building a new Central Station area. This is needed because of overdue maintenance, a growing number of passengers, a growing city and the desire to restore the original canals. The historic inner city and Utrecht The New Centre are two separated parts or areas of Utrecht; these parts will be connected (again) to form one coherent center. At the same time Jaarbeurs, which runs one of the main exhibition & conference centers in the Netherlands for national events, is adjusting to accommodate the growing digital world and focuses on the importance of 'live meetings'. Between 2014 and 2022 a variety of projects will be gradually implemented, ranging from the construction of the largest cinema in the Netherlands to a large-scale renovation of the Jaarbeurs passage and halls.

Against this background, the Municipality of Utrecht formulated an ambitious redevelopment plan together with Jaarbeurs and other stakeholders. Phase 1 of the project is in execution, while phase 2 is in the planning and decision phase (timeline 2015-2030). Phase 2, Utrecht The New Centre, concerns the redevelopment of the southern part of the area and includes the major stakeholder Jaarbeurs.

Figure 4.2: Map of area of phase 2 redevelopment plan



Source: Author's creation with stakeholder input.

4.3. Smart Sustainable Districts

The SSD project is partly funded by the Climate-KIC program of the European Union. Climate-KIC is one of Europe's largest public-private innovation partnerships focused on climate change. Its goal is to help cities in Europe transform into sustainable and resilient communities. It tries to achieve this by creating decarbonized and sustainable economies which should prevent catastrophic climate change in the future, and which should present a wealth of opportunities for businesses and society (Climate-KIC, 2017).

One of Climate-KIC's programs is called 'Smart Sustainable Districts'. Within the framework of the Climate-KIC flagship program Smart Sustainable Districts (SSD), the project aims to deliver decisive input on the sustainable transformation of Utrecht The New Centre. The research focusses on four priorities.

1. Hybrid integrated systems for heating and cooling at district level
2. Local use of locally produced renewable power
3. Green, climate robust and attractive
4. Clean and safe personal mobility

The SSD project is carried out with the help of partner organizations TNO, Deltares, Utrecht University, among others. The Utrecht Sustainability Institute (USI) contributes as knowledge and innovation broker to sustainable urban development, national and international, starting from the Utrecht region. It offers a platform for sharing knowledge, inspiration and social debate in close cooperation with governments, companies, knowledge institutes and societal organizations. In the SSD project, USI serves as project lead. The Technical University Munich (TUM) is also involved as they are one of the leading institutes in 3D city model development through CityGML. As such they designed their own conceptual framework which they call 'Smart District Data Infrastructure' (SDDI).

4.4. Smart District Data Infrastructure (SDDI)

This section discusses the Smart District Data Infrastructure (SDDI) in more detail. The SDDI aims to incorporate all the previous mentioned concepts of smart cities, SDIs, 3D geoinformation and 3D city models. The SDDI is organized in a modular structure in which actors, applications, registry, sensors, urban analytics, and a virtual district model make up the organizational and technical framework. Section 3.3 already described the different modules and what they consist of. This paragraph focuses on the characteristics of the SDDI, which include redundancy avoidance, well-specified data semantics, the virtual district model, interoperability, extensibility, functionality and transferability. Concluding is a comparison of the SDDI product with other smart city products.

One of the reasons that the focus from cities has been shifted to one lower scale, i.e. district, is the fact that in the district scale, it is more likely that overlaps of different sections and fields can be discovered. It is also more realistic to bring different stakeholders to the table on this scale and to discuss with them and find out what and where the barriers are. If smart and sustainable actions in one district are successfully applied, other neighbouring districts will no doubt be willing to look at this district and try to adapt the solutions in their areas.

Characteristics

In many cases there are datasets describing or related to a specific object. This object is often defined differently in different sources or by various providers. This leads to ambiguity and redundancy of the data which need to be interpreted later. For example, applications such as energy simulation, pedestrian flow simulation, applications involving real-time sensor observations in buildings all require to work with information about the districts' buildings which might be represented redundantly within each of the applications. In order to avoid data redundancy, standards play a crucial role. SDDI is designed based on standards from OGC and

ISO. For example, CityGML can be used to represent buildings just once for all of the applications mentioned above.

The challenging point is that the data in cities are often interpreted differently. This leads to the misuse of the data over time by different users. It is crucial to use data models which present meaningful information understandable by everyone, and therefore a well-specified data semantic is needed. Standards from ISO or OGC are good examples for this characteristic and are considered in the SDDI model.

The two aspects “redundancy avoidance” and “well-specified data semantics” are addressed by introducing a virtual district model (VDM). The VDM contains objects such as buildings, roads, city furniture, water bodies, etc. in addition to networks such as water utility, smart grid or transportation networks. (Percivall et al. 2015) argue that space is a principle method to organize the Smart City. Space (coordinates, geometry) is not the only method but semantic objects (with spatial properties) – as they are provided by the VDM – can be used as a common denominator for representing and organizing the information pieces from the various application domains of the Smart Districts. Detailed analyses of the SSD deep dive districts clearly show that nearly all thematic and sensor information are directly related to the objects of the VDM. Some sensors are even measuring properties of the real world objects (e.g. Smart Meters are measuring the power consumption of buildings). Hence, linking the sensors with the respective building objects and properties implicitly specifies the semantics of the sensor observations.

The VDM is a response to what is mostly missing in the data management of today’s other smart city initiatives. This is the management of the data through a common digital model of the physical urban environment as the information hub. This can be seen, for example, in IoT and Big Data analytics centered smart city concepts where the concept of linking the devices to a common data hub is lacking. Based on the experiences gained in the SSD project and through the work with various districts, a conclusion can be made that for almost all cases the districts need to work with or refer to district objects in one way or another. These objects are defined regarding their locations and their physical characteristics in the real world. Hence, it is necessary to have a virtual model of these physical elements of the area – whether it is just for a district or the entire city. Above, the VDM is also key to diverse types of simulations (e.g. energy, traffic, and environmental simulations) and to the estimation of the impacts of planned changes to the district.

Another characteristic is interoperability. According to ISO 2382-1 (c.f. ISO/IEC 10746-2:2009), the term interoperability is defined as “the capability to communicate, execute programs, or transfer data among various functional units in a manner that requires the user to have little or no knowledge of the unique characteristics of those units”. Interoperability is one of the most important characteristics of this model which covers the semantic and syntactic interoperability. This in fact is the key role of the SDDI which overcomes obstacles such as institutional barriers and avoids vendor lock-in, thus providing openness for extensions, and leading to the sharing of information.

The realization of the SDDI as a modular, open, and interoperable set of distributed functional components ensures the easy extensibility by new stakeholders, users, sensors, thematic information, and analysis tools. Furthermore, the model should not be stopped at the current development, as technologies are rapidly developing. The structure of SDDI is designed in a way which can be extended in order to meet the future needs and cases.

A standard solution ensures the functionality of the approach and model apart from the use cases. This means that the model is designed such that it can be used for different use cases.

What makes SDDI powerful is that this platform is not developed only to be implemented for one use case or one district but to be implemented in different places in similar ways (transferability). This characteristic of SDDI again is due to the extensive use of standards in this infrastructure. For example, there are many cities in the world, which have already developed the 3D model of their cities following the OGC CityGML standard.

The next section describes the requirements for the virtual district model.

4.5. Prototype Requirements

Actual, accurate and complete data are crucial for designing, modeling and planning in smart cities. The requirements are also dependent on the sort of application that is developed. For some applications, such as the modelling of urban floods, it is necessary to have knowledge about the underlying terrain in the form of Digital Terrain Models (DTMs) which require very high accuracy and resolutions. For other applications and/or models different requirements may be defined. Before describing the specific requirements for the Virtual District Model prototype for the SSD use case, a few general requirements of a virtual district model can be defined which are in relation to the before mentioned requirements to the smart city information systems.

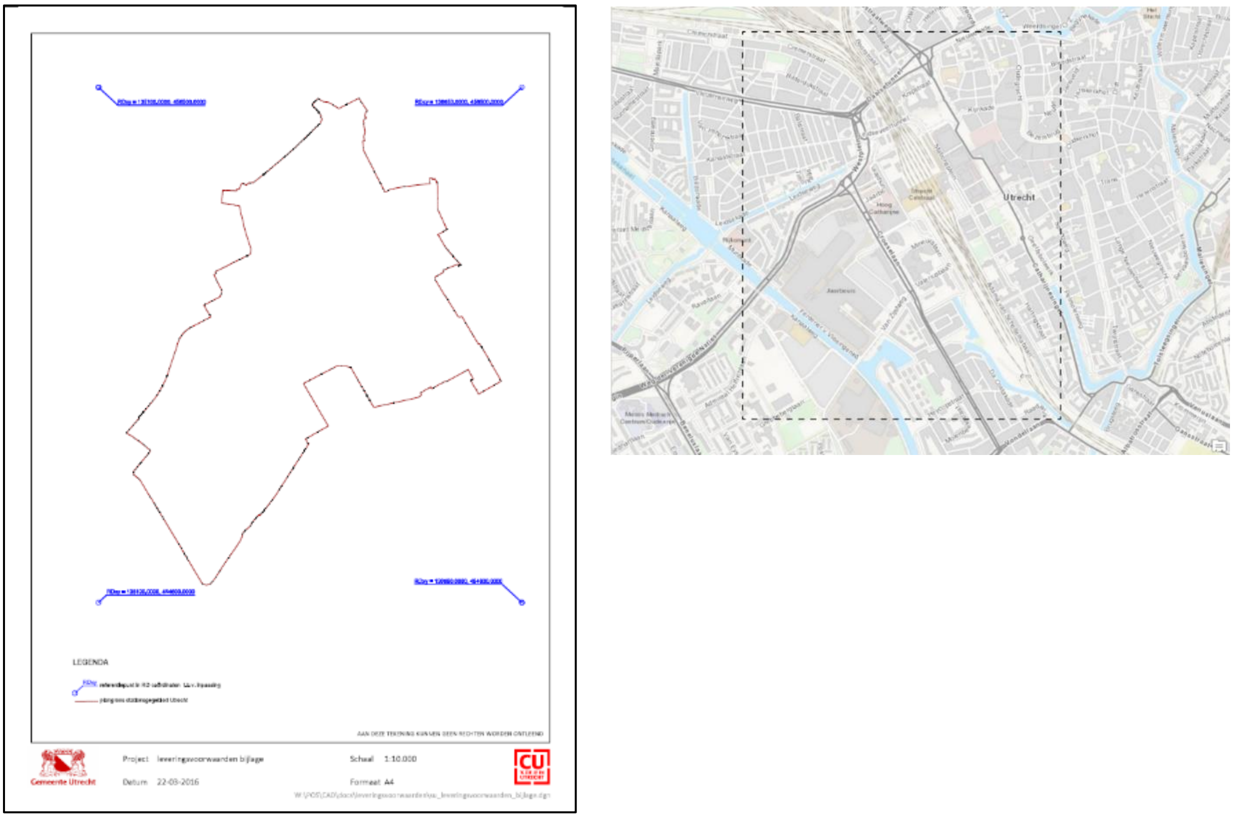
General requirements

General requirements for a virtual city model are (1) support for integrating heterogeneous sources of administrative geoinformation under the umbrella of the virtual 3D city model; (2) acquisition of 3D geodata for representative areas of the city and evaluation of the applied geodata capturing technologies; (3) adaptation and redefinition of administrative workflows to ensure model correctness in terms of the official cadastral database and to ensure sustainability and (4) Interactive systems for presenting and communicating contents of the virtual 3D city model to various target users and application areas (Dollner et al., 2006). The specific requirements of the VDM prototype for this thesis presented is developed for the project presented in this thesis. These are described next.

Coordinates/Area

Before the project started, the specific coordinates, coordinate system and area for all stakeholders was defined by the municipality (figure 4.3). This was done to ensure the interoperability of data. So that when data is exchanged between stakeholders, the data is referenced in the same coordinate system. Also, this makes sure that stakeholders are using the same project area. One of the requirements is that all data that is exchanged has to be in the RD New coordinate system. And that all data is provided with four x, y coordinates that mark the planning area and bounding box of the project.

Figure 4.3: Planning area and bounding box of station area.



Source: Utrecht Municipality, 2016

Data requirements

An important requirement concerns (spatial) data. Next to general requirements such as data quality, security, interoperability etc., some requirements specific for this project have been established. Among these are that stakeholder data is integrated in the Virtual District Model. The source data in this project concerns:

- Stakeholder data (non-spatial and spatial)
- Open data
- Spatial data
- (Possibly) real-time sensor data (e.g. air quality, wind, traffic etc.)

Level of detail

As the CityGML standard/data format offers several levels of detail that can be established, it could be a requirement that the virtual district model is constructed with a specific level of detail in mind. However, the during the course of the project it was decided that it would be wise to strive for a highest level of detail possible, depending on the available data. For the purpose of calculating solar potential of building walls, the requirement was LOD 2 for building blocks.

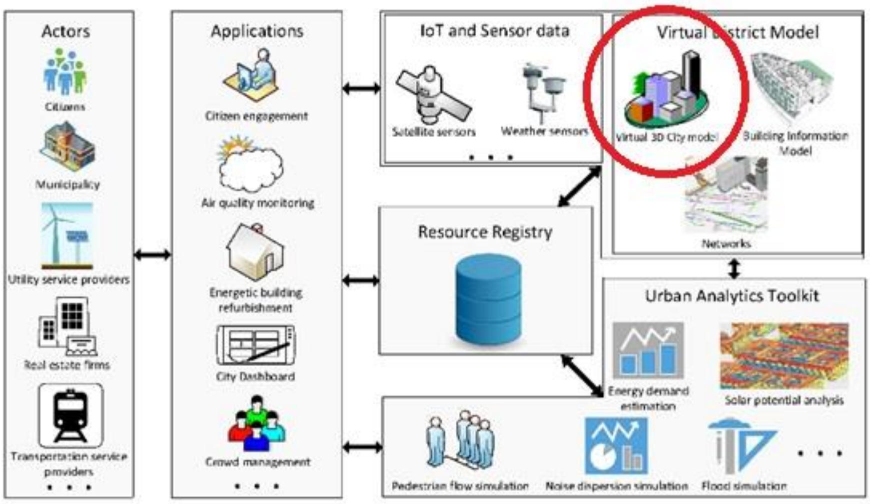
Visualization

Visual analysis is an important component of the requirements. The stakeholders in the project need to see how the future scenario is modelled. This can then be used for communication purposes towards citizens for example. Aesthetics are also important in this case. Also, the visualized scenario must be accessible by all stakeholders.

4.6. Design Scheme

The first step towards an SDDI is the creation of a virtual 3D city or district model (figure 4.4). It is not in the scope of this thesis to design a whole infrastructure.

Figure 4.4: VDM in the SDDI

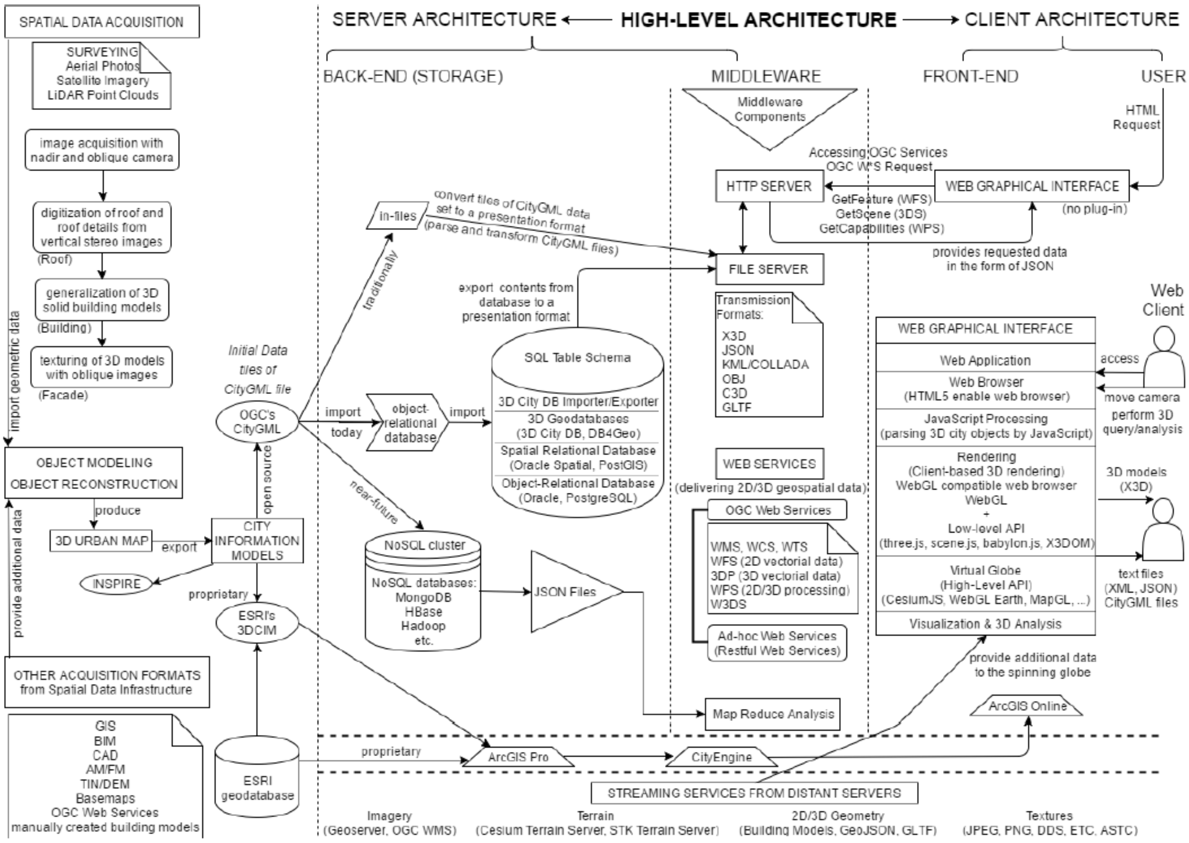


Source: TUM, 2017

To design a 3D virtual city model (VDM) for this project and its specific context, a design scheme is made, largely based on a workflow as identified by Guney (2016, figure 4.5). Although not all aspects of this workflow are relevant and/or used in this project, it shows the bigger picture of such a process. Several paths can be taken to reach the end-user.

Spatial and non-spatial data is acquired at first, which then has to be processed in a GIS to be able to do object modeling or object reconstruction. Using (spatial) ETL processes this spatial data can then be transformed into CityGML data. This data is object-oriented so can be stored in an object-relational database of which there are several available (PostgreSQL/PostGIS, Oracle Spatial, etc.). This provides the backend architecture. These databases can then export web friendly files such as KML/COLLADA and JSON or provide web services such as WMS and WFS. When the model reaches the end-user or the front-end it can be visualized in a web graphical interface such as Cesium.

Figure 4.5: Three level architecture + workflow for 3D geospatial applications on the web



Source: Guney, 2016, p.123

Chapter 5 will discuss this process/workflow in more detail and how it is applied for creating the virtual district model.

4.7. Evaluation Method

To assess and evaluate the proposed prototype, two aspects must be considered. On the one hand the SDDI can be assessed, on the other the virtual 3D city model. As the SDDI is not (yet) in actual practice and is merely a vision of a framework at this moment, it is difficult to evaluate it. This would only be a theoretical assessment. Section 3.3 showed SDI assessment approaches which can be used when the SDDI is in actual place.

The Virtual District Model that is created for the project however, can be evaluated. After its construction, it must be validated to check for errors before it is imported into a database. This can be done with the 3DCityDB tool which includes a validation function. This is done by means of an XML validation. Otherwise, errors in the data may lead to unexpected behavior or abnormal termination. Other tools for evaluation and validation can also be used. One of these is the 3D validation tool developed by TU Delft (val3dity). But as is tool can only handle relatively small model sizes (op to 50MB) it is not considered.

Next to that an assessment is made on the usefulness of the model, the source data and the methods used. And how the prototype meets the ideal smart city information system requirements.

The next chapter describes the design process of the prototype virtual district model.

5. Prototype Design

This chapter describes how the virtual city model can be built/designed and what steps are needed. It starts with defining the requirements of the model. Then, the way data can be acquired is explained, followed by how the data can be vitalized. Section 5.3 describes how the model can be visualized. Next, an overview is given of the software that is used for this project. Section 5.5 describes the initial steps taken to construct the model.

5.1. Data acquisition

The beginning of all 3D city models is the data acquisition (Sadek et al., 2015). Before the city model can be created, methods on how to acquire data have to be defined. For creating 3D models, a variety of approaches can be used, including building models, terrain models, landscape models. This is dependent on data sources and their scale and qualities.

Spatial data acquisition

In the case of this project, several spatial datasets were collected, mainly from already available open data sources such as the National Georegistry of the Netherlands (PDOK). Next to that, several stakeholders have provided data such as future building plans in the form of architectural drawings.

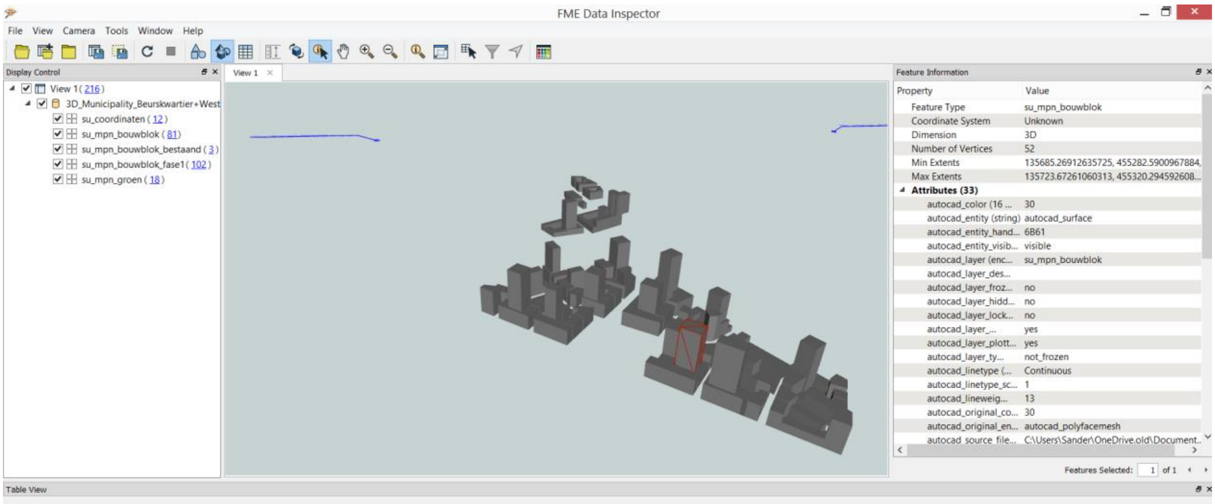
The 2D and 3D source data that is provided in the Netherlands by means of open data protocols and standards offer great potential for creating 3D geo-information (e.g. PDOK, Nationaal Georegister). This can even be enriched by additional data acquisition from for instance energy suppliers, housing companies, citizens etc. Some of the data that is available is already in 3D, such as the 3D Kaart NL, which is a digital topographical file in which all objects from the TOP10NL are visualized in 3D. Each file is a combination of 2D information of the Cadastre and the ‘Actueel Hoogtebestand Nederland’ (AHN), which is point cloud data obtained with Lidar technology (laser altimetry) from which a digital height or elevation model can be constructed. It consists of a raster DSM and DTM with a resolution of 0.5 meters.

Another method to create 3D data is for instance the 3dfier developed by the Technical University of Delft. This method takes 2D GIS datasets (e.g. topographical datasets such as the Dutch BGT) and combines them with point cloud data (LAS/LAZ, e.g. the Dutch AHN3 datasets). Output can either be in OBJ or CityGML. (https://github.com/tudelft3d/3dfier/wiki/General-3dfier-tutorial-to-generate-LOD1-models). This method is not included in this study however.

Stakeholder data

The municipality of Utrecht provided CAD/Microstation data of simplified future housing blocks.

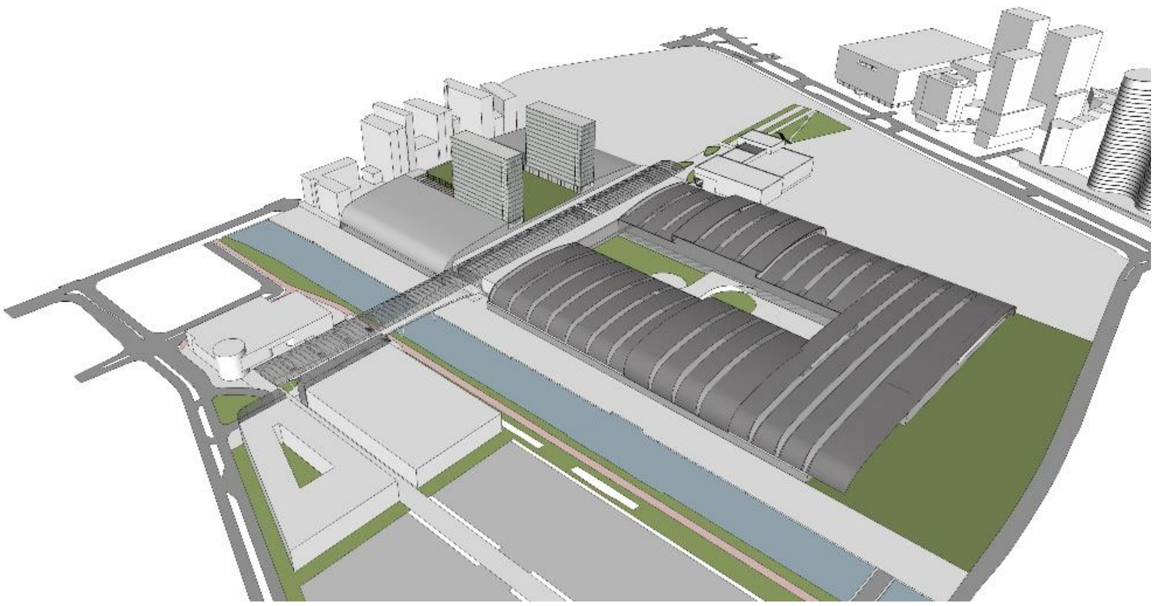
Figure 5.1: Screenshot of FME data inspector with municipality plans.



Source: Author

The Jaarbeurs stakeholder provided a Sketchup model of their proposed future buildings.

Figure 5.2: Screenshot of jpeg file provided with Sketchup files



Source: Author

Non-spatial data

Non-spatial data such as building materials, number of floors and data captured by smart meters and noise sensors, but also excel files, xml files, etc. were not required.

Historical and big data

Other types of data such as historical data and big data also exist and can be integrated. However, this lacked in the requirements. When the VDM is developed further these types of data can also be integrated if necessary.

Table 5.1: Used data for SSD project

Data source	**Data type**	**CityGML Modules**
No data		Appearance
3D Kaart NL	Multipatch	Bridge
3D Kaart NL	Multipatch	Building
Municipality	Dwg	Building
Jaarbeurs	Sketchup	Building
BGT	gml	CityFurniture
Result of other modules		CityObjectGroup
Scenarios (TNO, Deltares, UU)	Point/line/polygon	Generics
3D Kaart NL		LandUse
AHN/PDOK	DTM	Relief
3D Kaart NL	Multipatch	Transportation
No data		Tunnel
BGT	gml	Vegetation
3D Kaart NL	Multipatch	WaterBody

The data sources available provide a good starting point to develop a district model of the current situation in the area. To transform the available data that was acquired from the different data source type into the CityGML format, custom ETL scripts in FME had to be made.

5.2. Data vitalization

Now that it is defined how data can be acquired and what data this is, it is necessary to assess how this data can be vitalized (how it can be made 'alive'). This concerns data description, storage, association, maintenance, among others. This is necessary to proceed to data visualization.

Data storage

For the actual storage of the data, several options exist among which the use of regular folders, geodatabases and relational databases.

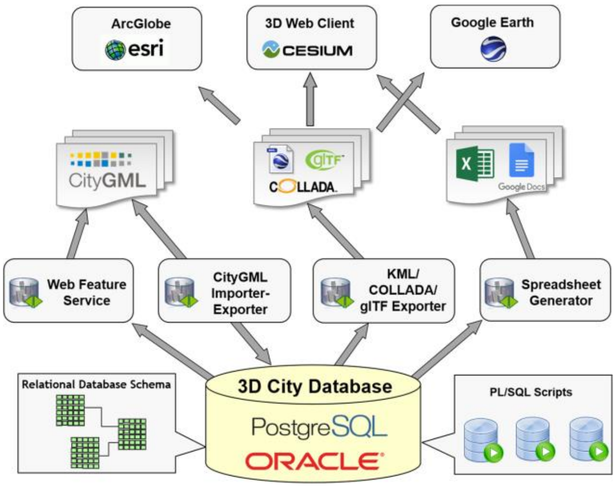
- *Esri geodatabases*

Geodatabases can serve as a first method to organize spatial data. ArcGIS offers easy to implement tools for that. Geodatabases offer many functionalities and can be of great value. These functionalities include creating, reading, displaying, querying several types of spatial and non-spatial data. Next to that they can create, edit, and alter the schema of simple tables, feature classes, feature datasets, raster catalogs, and raster datasets in file or personal geodatabases.

- *PostgreSQL/PostGIS database*

The SDDI framework and tools offer easy importing/exporting of CityGML files to an open-source object-relational database named PostgreSQL/PostGIS. The difference with Esri geodatabases is that this is a relational database. This software is therefore used to store the virtual district model. Next to that it can store (geo)data and/or map services to get and edit data from the database. The software package used for this is provided by the 3DCityDatabas software suite (figure 5.3).

Figure 5.3: Key components of the 3DCityDB software suite.



Source: Yao et al., 2018

Data description

Description and documentation of data is essential for ensuring that others that may need to work with the data can understand it and make sense of the processes that accompany the acquisition of data.

- *Catalogue/registry service*

Part of the SDDI is a catalogue and registry service. The virtual district model can be incorporated in this catalogue. An example of such a catalog application is the open-source GeoNetwork. It provides an easy to use web interface to search and query geospatial data across multiple catalogs. Other options are for instance CKAN which is an open source model for data storage and distribution, although it can also serve as data catalogue.

As this is a prototype, data maintenance is not considered to take part in the process.

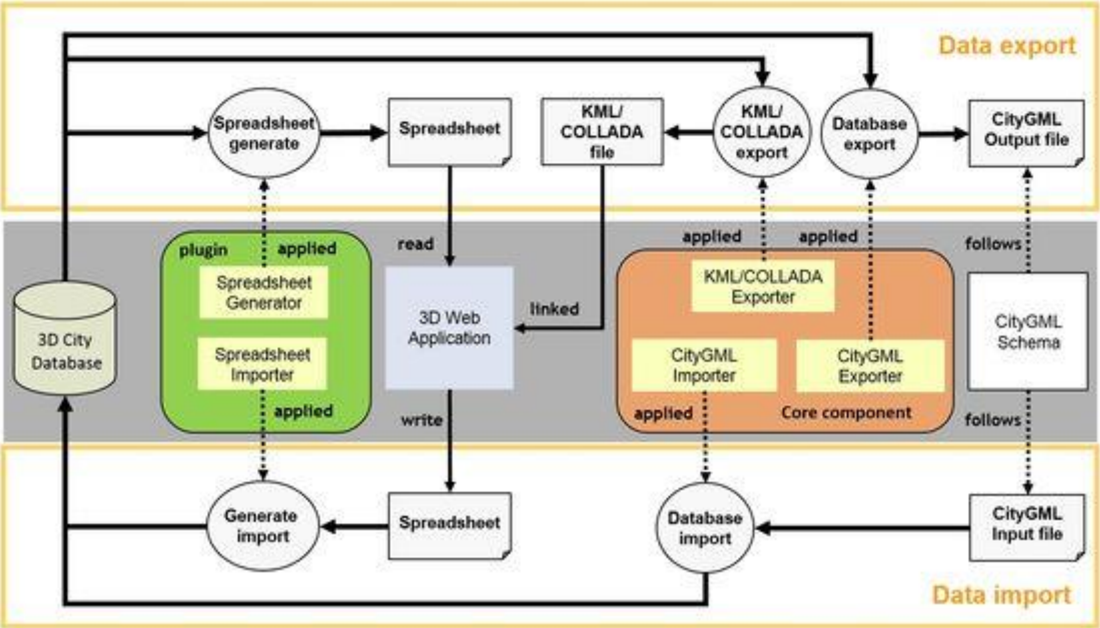
5.3. Data visualization

Now that the method on how to create the Virtual District Model is defined it is necessary to assess how the model can be visualized. Many tools for this exist. Also, many techniques can be used such as photorealistic visualization (e.g. using textured surfaces) and information visualization. As data for photorealistic visualization lack for this project, and the requirements are more specified for information visualization and applications, the latter is used.

CityGML models can be very large if they cover a great area or if the level of detail is huge. It is possible to render 3D views directly from CityGML, but this might not be feasible if the models are several Gigabytes large. Certainly, if they include fully textured buildings, terrain models and aerial imagery (Guney, 2016). Instead, CityGML models are of more use to represent and analyze 3D city objects, but not to directly present or visualize 3D city models (Rodrigues et al., 2013; Mao et al., 2012). Next to that, because CityGML is based on XML/GML schemas and as these might be complex, it is difficult for JavaScript applications to read them. Instead, a more suitable format like X3D, JSON, KML/COLLADA and WebGL can be used. The latter is used by CesiumJS for example. This preserves the richness, in terms of semantic information, of CityGML models (Gaillard et al., 2015).

To convert CityGML models to friendlier web formats, a number of methods can be used. In this case study however, the method is provided by the 3DCityDatabase application. One of its main features is the ability to export geometric information into different formats. The database can be approached by a variety of GIS softwares. But as the 3DCityDatabase Importer/Exporter tool is used it is a possibility to export KML or Collada files (see figure 5.4).

Figure 5.3: 3D web application architecture



Source: TUM, 2017

5.4. Software

The software used in this case study can be categorized and is listed below. A distinction is made between GIS software, Extract, Transform & Load (ETL) software, data management software and visualization software. The specific programs used are ArcGIS, FME, 3DCityDatabase tools and an open source web client Cesium. These are commercial (licensed) as well as open-source software. The choice for these software programs was made on their availability during the project and the options that they give.

GIS software

At the start of the project, most data were collected, edited and manufactured in ArcGIS. This included ArcMap, ArcCatalog and ArcScene, with all extensions available. Later on, ArcGIS Pro was used for data collection, editing and for some visualization purposes.

ETL software

To convert the acquired bottom-up data into CityGML, Extract, Transform & Load processes (ETL) are used with the help of Feature Manipulation Engine (FME) software. For this project the desktop version of FME is used. FME offers over 400 data readers, transformers and writers with which almost all possible data formats can be converted. It includes a CityGML reader and writer which is mainly used in this project (Safe Software, 2018).

Data management software

For managing the data created, the 3DCityDatabase software is used. 3DcityDB stores, represents, and manages the large CityGML datasets on top of a standard spatial relational database such as Oracle Spatial and PostgreSQL. It provides a Java frontend application named '3DcityDB Importer/Exporter', which allows for high performance importing and exporting of the CityGML datasets with arbitrary file sizes. It also allows exporting of the contents in the form of different visualization formats such as KML, COLLADA, and glTF, allowing the 3D objects to be viewed and interactively explored in the web applications. In this case the open-source DBMS PostgreSQL/PostGIS is used.

Visualization software

For eventually visualizing the cloud-based 3D web client Cesium is used. This is an open-source JavaScript library which can be used to create 3D globes and maps. It offers dynamic data visualization and real-time functionalities. As Cesium was developed, some open 3D geospatial formats originated such as 3D Tiles, glTF, quantized-mesh, and CZML. CesiumJS utilizes WebGL to provide hardware acceleration and plugin independence and provides cross-platform and cross-browser functionality. It allows the visualization of geographical data through OGC standards for data interoperability. It also allows the rendering of 3D models based on the glTF data format.

5.5. First steps towards an integrated CityGML based model

The previous sections outlined the requirements of the model, the data that will be used as input, and the software that will be used to create the 3D district model. This section describes the initial steps (selection, analysis, preparation and eventual integration of a number of datasets) for the creation of an integrated, semantic, three-dimensional, and CityGML-based virtual model.

It starts with the initial steps taken, working through the different softwares that are used taking into regard the workflow/design scheme. It commences with the work that was done in ArcGIS, followed by the ETL scripts that were created in FME to transform the data into the CityGML format. Then, the steps that were taken to manage the data with the use of the 3DCityDatabase are described. Ending with the visualization of the buildings module in the Cesium web client. Buildings represent one of the most relevant entities in an urban model.

Initial steps in ArcGIS (2D)

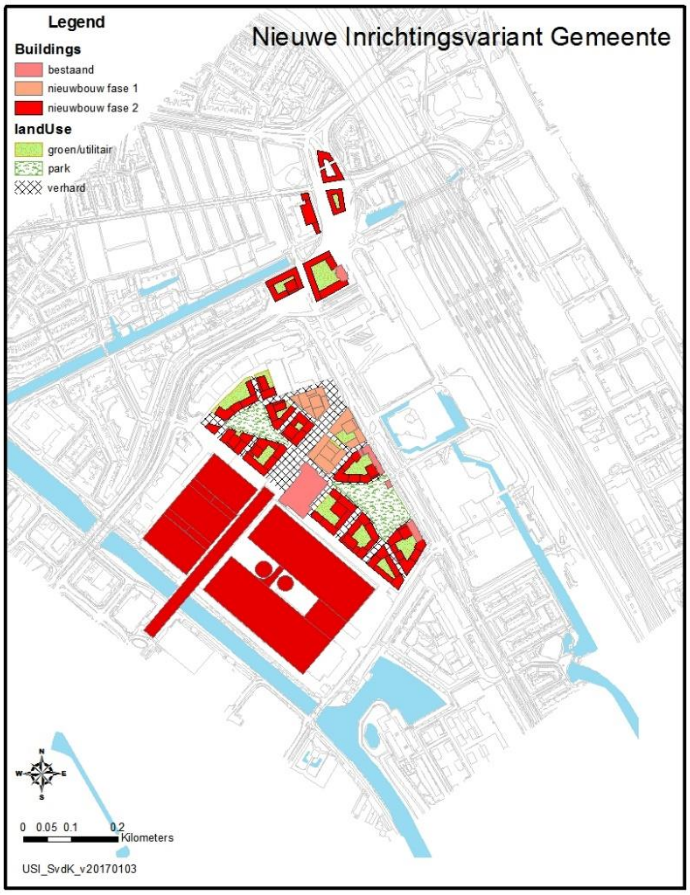
The first steps in the project were made in ArcGIS. This was primarily done to organize and edit the data that was acquired. Also, (preliminary) useful outputs as maps and 3D scenes had to be generated in order for the stakeholders in the project to discuss upon. It started with acquiring the data and making this data suitable for editing and analyzing in ArcGIS.

Stakeholder data (Jaarbeurs): Stakeholder data was provided by Jaarbeurs in the form of an architectural drawing/model of their future buildings in Sketchup. This Sketchup had to be transformed to a readable format for ArcGIS. This was done by using the Quick Import tool in ArcGIS. Because this model was not georeferenced, a spatial adjustment tool had to be applied to get the model in the right position.

Stakeholder data (Municipality): Other stakeholder data was provided by the municipality of Utrecht. These were the future planned buildings for the area. They were acquired in a CAD format (.dwg). A transformation had to conducted for these data as well. ArcGIS offered this tool. As it was georeferenced in the RD New coordinate system and within the required bounding box coordinates, it landed on the correct location.

Open data: The 3D data from PDOK was provided in Esri multipatch format with several Level-Of-Details. This could easily be imported into ArcGIS without any data conversion necessary.

Figure 5.5: 2D display of stakeholder (Jaarbeurs & Municipality) data



Source: Author's creation in ArcGIS with stakeholder input.

Figure 5.6: 3D display of project area with future buildings.

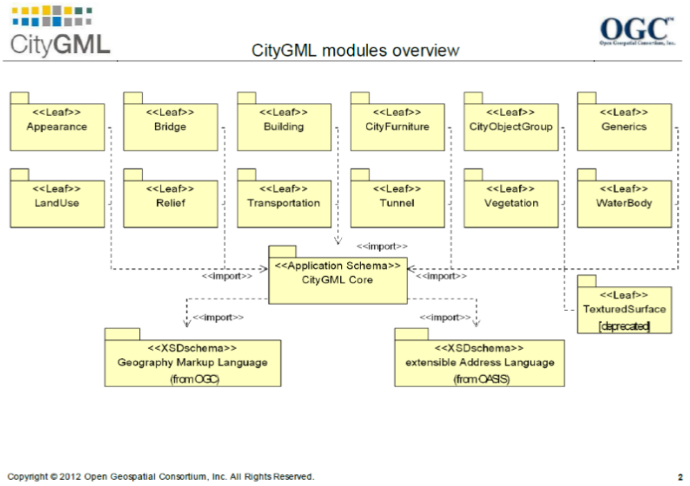
Source: Author's creation in ArcGIS with stakeholder input.

Resulting from the collection of acquired data in ArcGIS is a geodatabase that is populated with these data and hence serves as input for the transformation tools in FME. The next paragraph describes the steps taken in FME.

Data transformation

This paragraph describes the steps taken in FME. FME is used to transform the original data into the CityGML format. It is important to understand that CityGML is made up of modules (figure 5.7)

Figure 5.7: CityGML 2.0 modules overview



Source: OGC (2012, p.2)

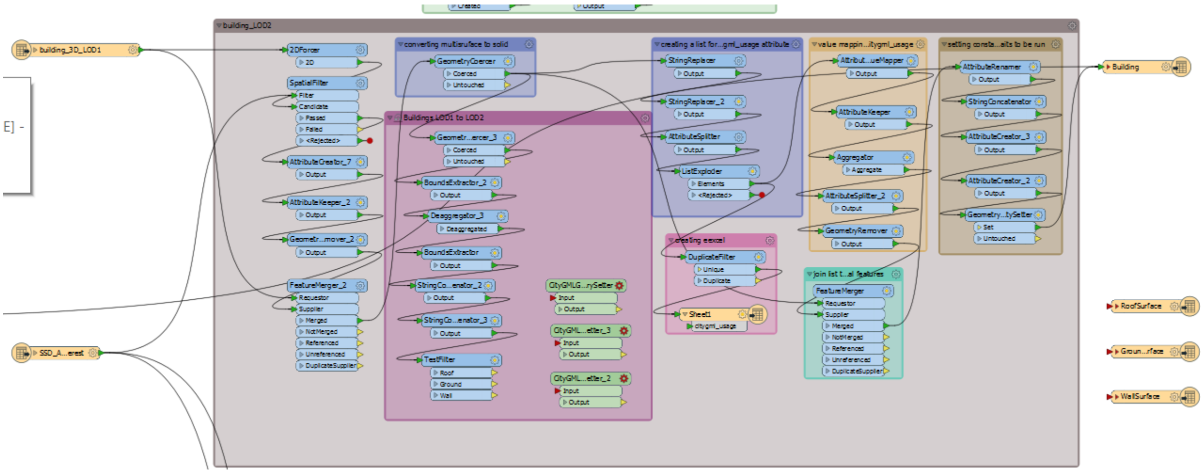
These modules form the basis of modelling in CityGML. Therefore, an assessment is made to which extent the available data compares with these modules (see table 5.1).

Table 5.1: Module and data routing for SSD project

CityGML Modules	**Original data source**	**Original data type**
Appearance	*No data*	
Bridge	3D Kaart NL (PDOK)	Multipatch
Building	3D Kaart NL (PDOK)	Multipatch
	Municipality	Dwg
	Jaarbeurs	Trimble Sketchup
CityFurniture	*No data*	
CityObjectGroup	*No data*	
Generics	*No data*	
LandUse	3D Kaart NL (PDOK)	Multipatch
Relief	AHN (PDOK)	DTM
Transportation	3D Kaart NL (PDOK)	Multipatch
Tunnel	*No data*	
Vegetation	*No data*	
WaterBody	3D Kaart NL	Multipatch

To transform the source data, custom ETL scripts have been created. A screenshot of the conversion of the buildings source data into the CityGML building module is given in figure 5.8

Figure 5.8: Screenshot of FME script for CityGML's building module.



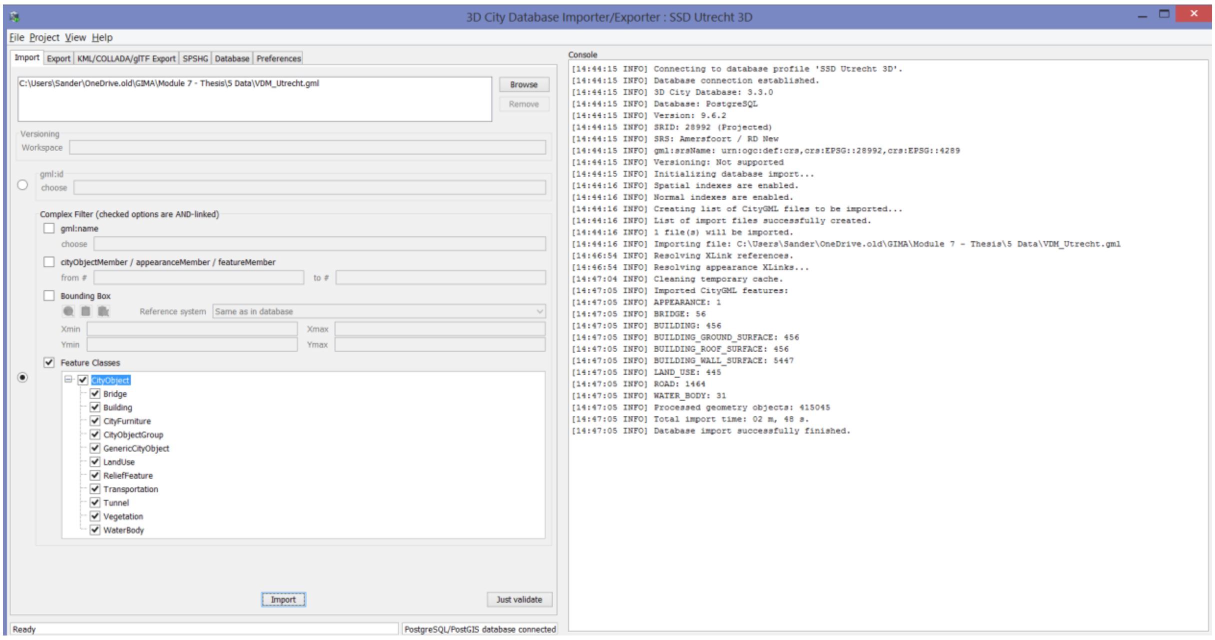
Source: FME Workbench

When the FME scripts have run, the resulting output is a CityGML file containing several modules, namely Bridges, Buildings (LOD 1 & 2), City Model, LandUse, Transportation, Waterbody. Next, the 3DCityDatabase software can be used to validate this file and to store the CityGML model in a PostgreSQL/PostGIS database.

3DCityDatabase steps.

To install and use the 3DCityDatabase the necessary documentation can be downloaded from the website. As this is a free-to-use software it is rather easy to start working with it. Manuals provided the steps that had to be followed. In short, these are (1) checking requirements, (2) preparation of data (which was done in FME), (3) importer/exporter tool installation, (4) 3D City Database setup, (5) CityGML validation and import, (6) KML/Collada export.

Figure 5.9: Screenshot of Importer/Exporter tool application



Source: 3DCityDB

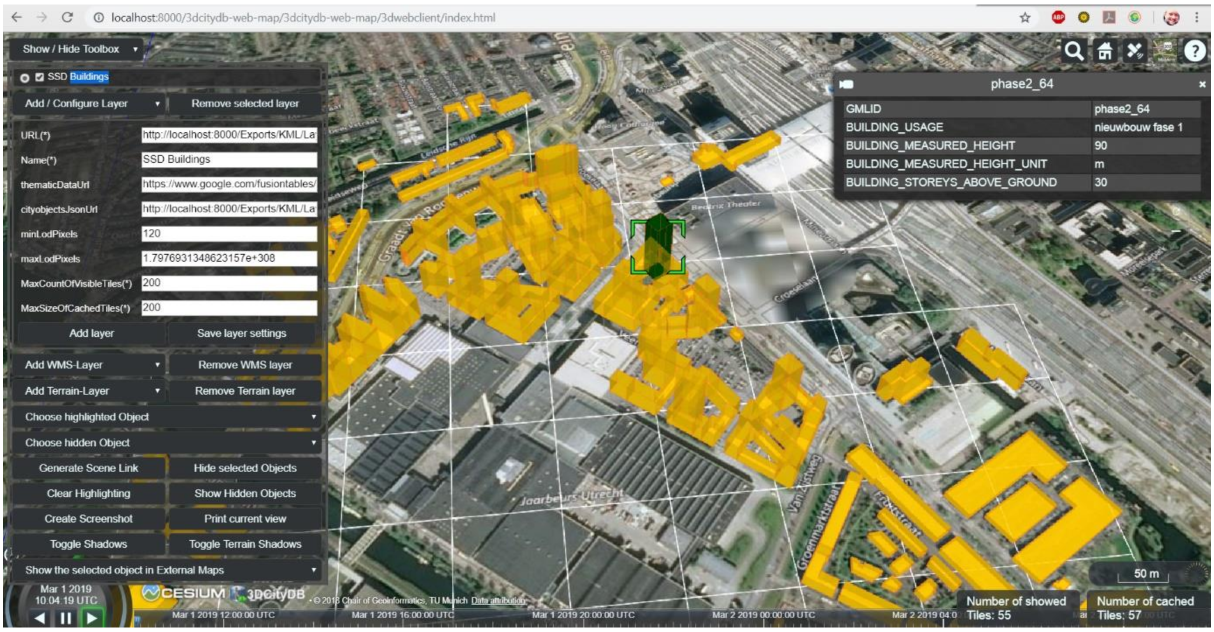
Cesium steps

To demonstrate the VDM in an online 3D visualization tool, a selection was made to display the buildings in the VDM. The 3D City Database software package provides an interactive 3D web client (3DCityDB-Web-Map-Client) using the Cesium Virtual Globe framework which is based on HTML5 and WebGL technology and which runs in the most modern browsers and on different operating system. The 3D web client links 3D visualization models exported in KML/COLLADA/glTF format with online spreadsheets exported using the 3DCityDB Spreadsheet Generator and allows interactive viewing and querying objects and their thematic data.

In order to run the 3D web client, a web server to host the client files must be set up. This can be done by running a local web server on top of the Node.js runtime environment (e.g. http://localhost:8000/3dcitydb-web-map/3dwebclient/index.html). The web client can then be opened, and data can be loaded (KML and spreadsheet data).

An example of the model is shown in figure 5.10. As no web server was at hand for the project, the model is not available online unfortunately.

Figure 5.10: Screenshot of a selection of buildings with attributes in Cesium.



Source: Cesium web client

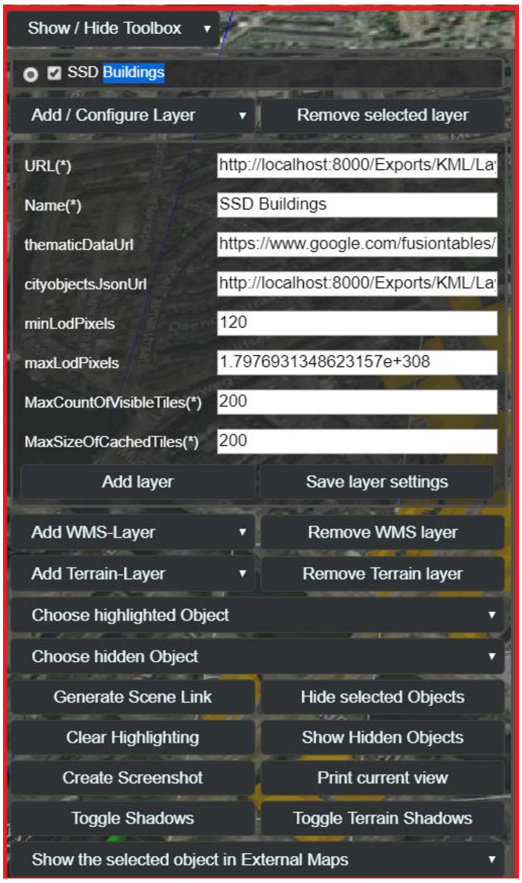
Prototype details

The eventual prototype in the Cesium web client shows the current and planned buildings (future scenario) in a 3D geographic context. The application has several options to enrich the scenario with other data, or to manipulate the view (figure 5.11 and 5.12).

Figure 5.11: Toolbox in Cesium webclient.

Source: Cesium web client

Figure 5.12: Toolbox Cesium webclient close up

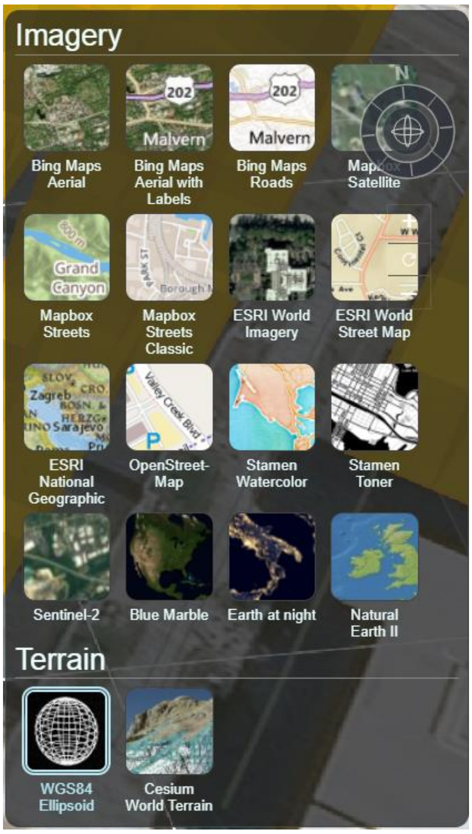


Source: Cesium web client

As can be seen additional layers can be added, such as WMS and Terrain layers. Next to that, objects can be highlighted or hidden. Also, screenshots or prints can be made from the current view. There is even the option to toggle shadows of objects and terrain providing a preliminary analysis on shadow casting. The final option is to show a selected object in external maps such as Google Streetview, OpenStreetMaps, BingMaps Oblique View and Dualmaps.

Another feature is the ability to change the background base map (figure 5.13). As can be seen the selected background map is a WGS84 Ellipsoid, providing for a 3D world view when zooming out, much like Google Earth. But one can change the imagery to their preferences.

Figure 5.13: Cesium webclient base map options



Source: Cesium web client

The next section discusses the validation and assessment of the prototype.

6. Prototype Evaluation

The previous chapter has explained how data was acquired, vitalized and visualized. Also, the used software was described and eventually the first steps taken towards an integrated Virtual District Model. This chapter describes the model's validation and an assessment is made on several parts in the process.

6.1. Validation

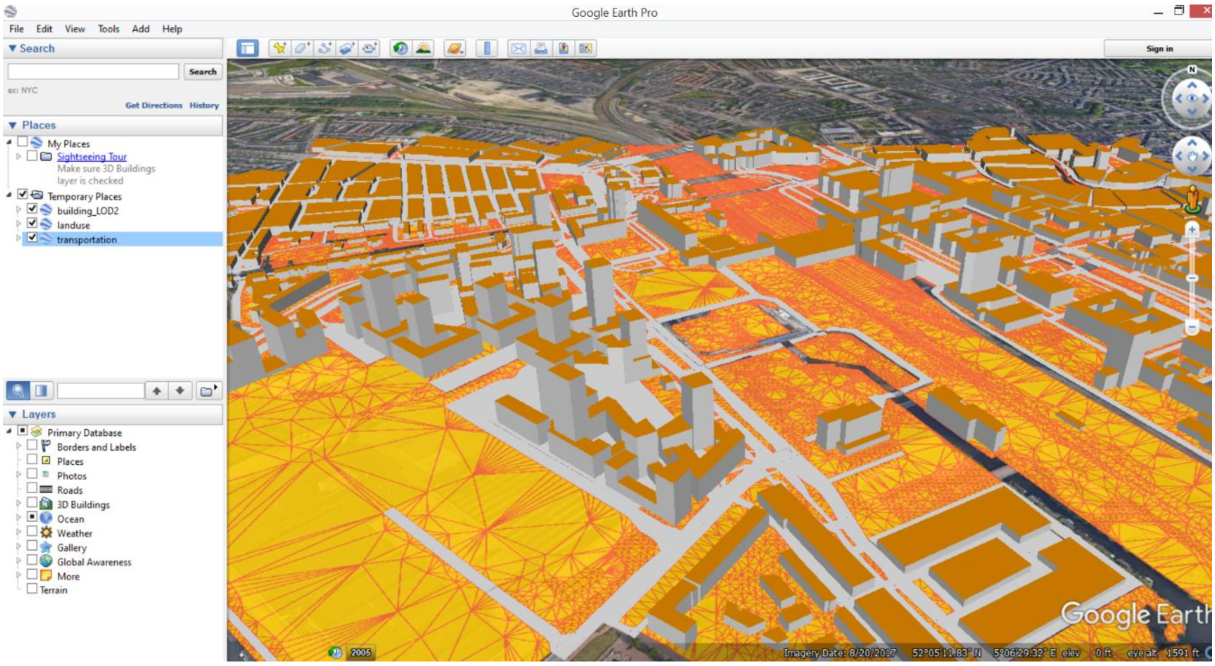
Several tools exist for the validation of CityGML-based virtual 3D city models. Three checks can be distinguished: syntax, geometry and semantics (CityDoctor, 2018). A syntax check makes sure that the data is conformant with the OGC standard document for CityGML. A geometric validation can check if there are no topological or geometrical errors such as holes in the model, and that for instance buildings can be considered as solids or as boundary surfaces. A semantic check ensures if the attributes are in relation to the geometry, for instance the orientation of buildings (are roof surfaces directed to the sky?). Not all checks have been made for the result of the prototype because not all tools were suitable or at hand. The validation function in the 3DCityDatabase Importer/Exporter tool was used.

Before importing into the database and using the CityGML files, a validation has to be made against the official CityGML XML schemas. This can simply be done in the Importer/Exporter tool provided by the 3DCityDatabase package. The result for the city model that was created is that it is valid. It is recommended that only CityGML files that have passed the validation are imported into the database. Otherwise errors in the data may lead to unexpected behavior or abnormal termination.

Other tools to validate the created CityGML file also exist. One of these is the 3D validation tool developed by TU Delft (val3dity). But as is tool can only handle relatively small model sizes (op to 50MB) it is not considered.

Another way of validating the outcome is to check the resulting files. Figure 6.1 shows the exported KML files of the buildings (LOD2), landuse and transportation modules in Google Earth Pro.

Figure 6.1: Screenshot of KML exports in Google Earth Pro



Source: Author's creation.

A visual inspection, however, might not be sufficient as there are often invisible flaws in 3D city models. But it shows a result that stakeholders can already interact with and discuss about.

The next section assesses the steps taken in the process, the case study, the design scheme and the outcome.

6.2. Assessment

Now that the resulting model is validated, an assessment can be made on several factors. In this paragraph the methodology, the source data, the usefulness of the model and the function it can have to serve as the backbone of a smart city information system is discussed.

Methodology

The design that is proposed and the methods that accompany it, can be copied for other districts and other purposes. It takes open data, stakeholder and other sources of data and transforms it to the CityGML data type standard. For the open geodata that was used as input, it can be applied to larger areas than the one in the project. The same scripts in FME can be used. For stakeholder data however, it depends very much on what the stakeholder delivers. If this is CAD or Sketchup data, or any other type of data, custom transformations might have to be made. In general, it showed that it was useful to first collect, edit and organize in a GIS before serving it as input for the FME scripts.

However, acquiring data the way it was done for this case study might not be the best way. More advanced and useful methods are evolving such as the 3Dfier, developed by TU Delft. It depends on the source data which is discussed in the next paragraph.

Source data

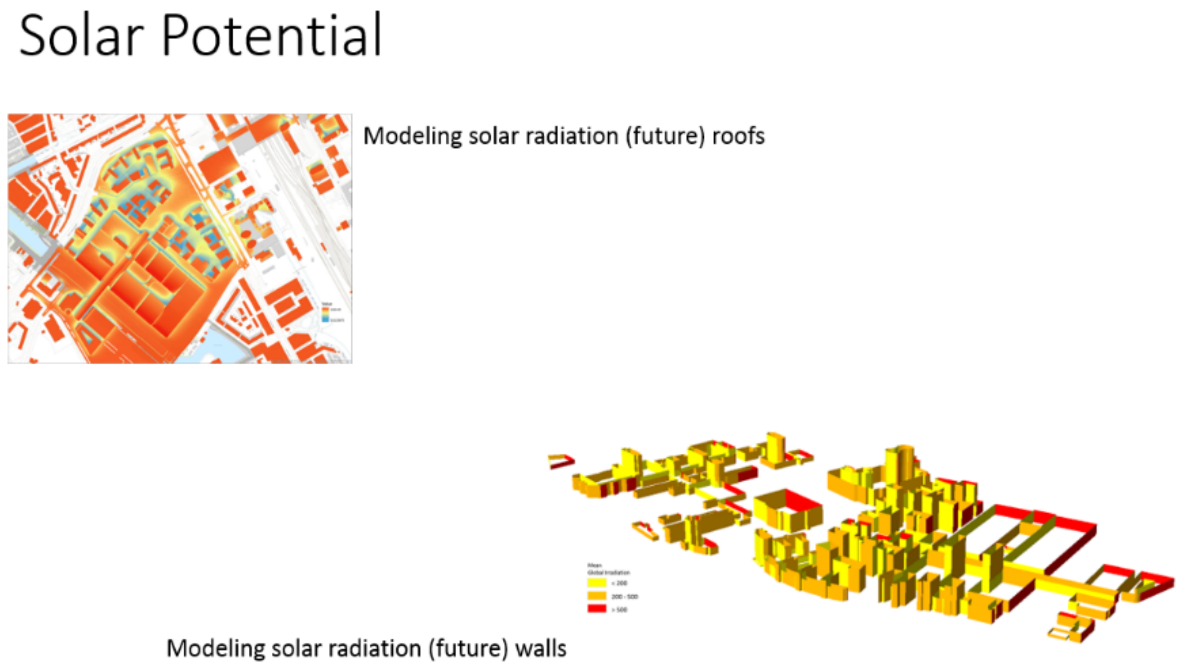
When assessing the actual source data used it can be said that the open data from the Dutch government is soon outdated. The data used in the project are from 2017. Especially in a rapid developing area such as the district of the project, where new buildings are constructed all year round, this might soon lead to outdated city models. And as this data is not provided as a service (e.g. WFS, API), but as a download which is not regularly updated it is doubtful if this is the best source to get data of the built environment. Next to that, not all CityGML modules are supported, data for thematic modules such as tunnels for instance, is lacking. Also, the data provided is of simple detail. The buildings are merely blocks (LOD1) with no roof details for instance.

The stakeholders source data that was used differed from stakeholder. The municipality data provided simple square building blocks in CAD format. This was fairly easy to transform. More detailed plans were welcome but at this stage they weren't formed yet. The Jaarbeurs Sketchup data however was a different story. At first, this data did not have any georeferenced, so a manual spatial adjustment had to be made. Secondly, it was difficult to filter out separate relevant buildings from this file in FME and transforming it into CityGML. The result is several buildings as one building/CityObjectMember. Next to that, during this study, Sketchup wasn't supported anymore by FME.

Usefulness

Already during the course of the project, a 3D virtual city model proved to be useful for developing future scenarios and measuring the effects such scenarios may have on an area. For instance, the wish of using building walls for solar panels was expressed. Because the buildings are provided in LOD2, a stakeholder in the project (Technical University Munich) was able to do a solar power potential calculation for the walls (figure 6.2). Other stakeholders (e.g. Deltares) were able to calculate water run-off based on the model.

Figure 6.2: Simulations with CityGML LOD1 and LOD2 models



The stakeholders in the project had their own tools, applications and software for that, but the backbone for these applications was the 3D model in CityGML. Although the model is not yet perfect it was useful enough. Other applications, especially considering smart city development can also make use of the virtual district model. Next to that, a shift from making 2D GIS analyses to 3D analyses can be made, providing even greater insight. For this to work well, it is however recommended to have a geometrical correct model with no errors. Also, the model is suitable for integrating other technologies such as sensors and other real-time data sources, because it is based on open standards.

Lastly, CityGML can be considered as a base information model for virtual 3D city models, but for specific applications extra information is needed that are typically in close interaction with the CityGML base information. Some examples: for environmental simulations like noise emission mapping need information about noise absorption of surfaces. Utility networks need to represent pipes, pipe tunnels, connectors, transforming devices etc. Cultural heritage needs to augment objects by their heritage and history, possibly considering the development along time. To extend a CityGML model, Application Domain Extensions can be used (ADEs), such as the already existing Noise ADE and Energy ADE. Using CityGML for building a model of the urban environment is a first step for the applications and deployments described above. It can be considered as a modern-day equivalent of having a 2D map (Percivall et al, 2015) and hence enables many functions.

6.3. Comparison with smart city information system requirements

To finally assess if the prototype meets the requirements for the ideal smart city information system as defined in Chapter 2, the list of requirements is mentioned here once again:

- *Facilitating the organization of the data, applications, services, sensors of a city in a common framework and technological ecosystem (clear and stable architecture)*

The previous chapters have described the development of a prototype smart city application, in this case a 3D city model, which is part of a Smart District Data Infrastructure (SDDI). This type of Spatial Data Infrastructure can be regarded as the framework in which data, applications, services, sensors in smart cities can reside. The 3DCityDatabase as the data registry in which the 3D city model is organized and stored and which can be used for certain applications for urban analytics. A Cesium webclient as a smart city application to visualize 3D city models and its thematic attributes. However, the limitations of the prototype are as such that services (e.g. WFS) and the incorporation of IoT and sensor data have not been established.

- *Low entry barriers / low investment risks / high flexibility*
    - *low operation costs (open source and flexible software)*
    - *no migration costs, because existing systems and platforms are interfaced*
    - *easily and incrementally extendible: datasets, applications, services, and tools can be added and used anytime and by third parties (open standards/open access)*

By developing the prototype, it was shown that general costs for developing such an application can be considered quite low as opposed to the usual large commercial projects. Costs that can be distinguished are man-hours, software licenses (ArcGIS and FME), hardware. Existing software and hardware can be used, as well as existing systems and platforms. No new software or hardware has to be developed specifically. As mostly open data and some open source software programs have been used, the prototype is easily extendible. However, the development of such a smart city information system needs dedicated, skilful people as the construction of a 3D city model in CityGML is still quite complex and needs expertise.

- *Facilitation of easy and user-friendly access to city resources (dashboards, maps and other communication tools)*
    - *to the customer and its partners; also to the public (practical use and user experience) (webportal for communication, citizen engagement)*
    - *accessibility to (geo-)data and information (online data catalogue with download option)*
    - *Providing an intuitive 3D geographic view onto the city resources (3D webviewer)*
    - *User clients incl. 3D visualization run on any platform, operating system, and browser without extra installations; incl. mobile systems (domain application layer)*

The outcome of the prototype is a 3D geographic view of some of the city's resources. Data that has been used and produced is in an open and interoperable format which provided easy accessibility to data and information. Hence, the prototype facilitates an easy and user-friendly access to city resources. However, a reference can be made again to the 'map literacy' of users. Users must have some understanding of what is visualized and how they can use it. Also, a digital skillset is needed to use the client. Next to that, users must have internet connection and the platforms available on which the 3D visualization can be run. At the moment, not all systems support this to the fullest.

- *Support of planning and decision making*
    - *Visualization of newly planned buildings in the geographic context into a Virtual District Model (digital twin)*
    - *Facilitation of urban simulations like solar potential analysis, building energy demand estimations*

Meeting the requirement 'Support of planning and decision making' is established by providing the visualization of newly planned buildings in a geographic context in 3D city model as was shown earlier on. Even the project's stakeholders were able to run some urban simulations with the model. However, the visualization is a first step towards a more integrated 3D city model and is still limited in its capabilities. Also, to provide for better urban simulations the model can be linked with other types or sources of data such as energy labels, climate sensors, air quality sensors and such.

6.4. Comparison with other 3D Smart City Models

This paragraph compares the prototype with the 3D city model examples mentioned in section 3.8. The comparison is made based on functionalities and (geo-)data and information that has been visualized. Then, it is concluded what should be done or added to the prototype in order to enhance it and develop it further

Common characteristics

After briefly reviewing the four examples of 3D city models (Rotterdam, Gothenburg, Berlin and New York) a few common characteristics of the applications have been distinguished. These are listed here once again:

- Free, online access
- Open data based
- Specific functionalities
- Semantic and thematic information
- Interactivity
- Citizen engagement
- Large projects

When comparing the prototype with the cases described in section 3.7. and referring to the common characteristics, the prototype can still be greatly enhanced. For instance, it is not yet freely accessible online but only locally. The prototype is mainly based on open data so that's a characteristic that is common, but some data sources are not necessarily shared as open data, such as the future plans of the municipality and the Jaarbeurs. Also, the provided examples each have their own distinct functionalities, the prototype does not have any specific functionalities yet except from the ones mentioned before. It does show some semantic and thematic information however. The prototype is also interactive in the option to query objects and their information. Although the development of the model was part of a larger European project, the work done for the 3D model specifically was not part of a large (research) project spanning multiple years, hence the limited functionalities and the missing common characteristics of the shown examples.

Future Needs

To further develop the prototype and use it in building smart cities, a few essential needs to have to be fulfilled. As the prototype at the moment is not hosted on any server, it is necessary to provide both a database as a web server. Also, the prototype model has to be semantically and thematically enriched with attribute and object information. Next to that, ideally it concludes dynamic data such as real-time sensor information and is it able to also integrate BIMs.

7. Discussion and conclusion

The previous chapters have described smart city concepts, geospatial information and technology, the case study used, a prototype design and the prototype evaluation. This final chapter provides a discussion and a conclusion.

7.1. Discussion

This section discusses if the objectives have been met and what drawbacks and/or criticism on this topic and the methodology can have. To refresh memory, the objectives were:

- Understanding the relation between smart city concepts and geospatial concepts
- Define the ideal smart city information system
- Give an overview of geospatial information systems and applications
- Describe and develop a prototype geospatial information model
- Evaluate the prototype against the ideal smart city information system

Chapter 2 and 3 have dealt with the first three objectives and have aimed to enhance the understanding of smart city concepts and geospatial concepts. Although it was not a deep dive into smart city or GIS theory, it discussed the major approaches, technologies, trends, challenges and applications. A definition was formed what the ideal smart city information system must consists. Although this is not a definitive description, it is argued that spatial information should serve as the backbone of such a system.

Chapter 4 introduced the case study for this thesis and describes the Smart Sustainable Districts project carried out in Utrecht with several stakeholders. The aim of this project was to develop future scenarios and measure its consequences. To do so, a framework and methods for constructing a 3D Virtual District Model (VDM) were described and designed. The VDM, being part of a Smart District Data Infrastructure, serves as the basis for some smart city applications. Requirements for the model were described, although these were not so major. These could have been defined in more detail. Next, a design schema was proposed and an evaluation method. This chapter made sure to describe why the proposed prototype in this thesis was chosen.

Chapter 5 and 6 carried on with the design process and the evaluation of the model. Methods on data acquisition, data vitalization and data visualization were defined, and the software used for the project was described. Then, the first steps towards an integrated CityGML model were made with use of the software. Here the practicalities are described. These two chapters aimed to answer to objectives four and five.

Answering the research questions

From the objectives the research questions for this thesis have been distilled in the introduction. These are listed again here:

The main research question is:

> *What is the role of geospatial technologies in building smarter cities?*

The research question is divided into several sub questions. These constitute:

> *What is the ideal smart city information system and what are its requirements?*
> *How can available geospatial technology and data contribute to building smarter cities?*
> *What is needed to build a prototype geospatial information model?*
> *How does the prototype compare to the ideal smart city information system*?

The sub questions are answered here while the main research question is answered in the next section (7.2 Conclusion). In Chapter 2, the ideal smart city information system is defined and its subsequent requirements. These are the facilitating the organization of the data, applications, services, sensors of a city in a common framework and technological ecosystem. Low entry barriers / low investment risks / high flexibility for implementing such a system. The facilitation of easy and user-friendly access to city resources (accessibility and visualization of urban data) and support of urban planning and decision-making.

In chapter 3 the contribution of geospatial information and technology to the ideal smart city information was discussed. Geodata i.e. data with a geographical component, can be used to generate information which is relevant (or even vital) for decision-making processes. GIS tools can visualize the data that is gathered and used in smart cities in a way that is understandable and easy to grasp. It also offers many kinds of analysis possibilities and domain-specific applications which are unique for geo-information and highly relevant for smart city processes. Using 3D city models over 2D maps can greatly enhance the abilities for realistic simulations and specific 3D analyses. It also provided an intuitive view of the city in a geographic context. Next to that, the underlying Smart District Data Infrastructure (SDDI) served as technological framework. This type of Spatial Data Infrastructure can be regarded as the framework in which data, applications, services, sensors in smart cities can reside

The consequent chapters have described what is needed to build such a 3D city model using a specific methodology, open data, and different kinds of software. The design that is proposed and the methods that accompany it, can be copied for other districts and other purposes. It takes open data, stakeholder and other sources of data and transforms it to the CityGML data type standard. Already during the course of the project, a 3D virtual city model proved to be useful for developing future scenarios and measuring the effects such scenarios may have on an area. For instance, the wish of using building walls for solar panels was expressed. Stakeholders were able to use the 3D city model that was constructed to apply a calculation on the most suitable walls as a prime example of the added value of 3D GIS analysis. This means that the prototype is able to support urban planning and decision-making processes. The prototype can serve as an immersive tool for city planners and other stakeholders to test, visualize, and communicate their ideas to the public.

Drawbacks

Although the proposed prototype seems ideal as smart city information system, it has some negative aspects as well. One of these is the complex method to build a virtual 3D city model. Extensive knowledge on UML schemas, FME software, databases, web servers and applications is needed. Also, soft- and hardware has to be available. An FME license is required for instance, a database has to be hosted, as well as a web server. During the course of the SSD project this seemed difficult to arrange with the stakeholders.

Criticism.

As with many concepts and theories, there is also criticism on the smart city initiatives. For instance: conflicting (strategic) interests might lead to tunnel vision and ignoring other methods to develop urban areas (Greenfield, 2013). Next to that, smart cities can be compared to the scientifically planned (blueprint) cities of the 19^{th} and 20^{th} century. Although these blueprints were mainly related to spatial planning, a comparison can be made with that people might not be able to participate to shape the city they live in (Sennett, 2012). Negative aspects of implementing smart city technology and networks might be underestimated (Graham & Marvin, 1996) and big data collection and analytics might result in problems with surveillance and privacy issues in smart cities. These critiques show that there is also skepticism about the smart city concept. Therefore, urban planners and alike should consider all aspects when trying to develop a smart city and try to come up with some rules and laws perhaps.

Final thoughts

The benefits of having a 3D visualization for these purposes are clear and powerful. However, the role of 3D in other applications such as analytical capabilities is still not clear at all times. Easily creating shadow casting, view sheds and solar analyses, etc. are well documented uses of 3D models but the question remains if these applications will be used after all. Also, additional analytical capabilities have to be explored. Part of this is making sure that the prototype is more than just a visual representation of the city but that it is instead integrated with real-time sensor data for example, thus creating a more dynamic decision-making tool.

The integration of data deriving from heterogenous sources is fundamental for obtaining complete up-to-date and detailed city models for in-depth analyzing the city, visualizing it and supporting any kind of application. Prior in such integration is the integration of 3D city models, representing the urban environment in a multi-dimensional model, with (geo-)data derived from open data topographic and administrative registrations, sensors, construction management (BIM), etc. A methodology for achieving a smart integration of these data sources and potentially other sources based on open standards and certain tools has been used worked out in this thesis. The resulting prototype has the potential to be used for research in smart city analysis with the cooperation of stakeholders.

7.2. Conclusion

This thesis has aimed to address the role geospatial technology in building smarter cities by providing a literature review and constructing and reviewing a prototype information system that is part of a case study. It shows that the ideal smart city information system is a system that incorporates spatial information and geospatial technologies. From a practical point of view there is a need of a holistic approach to technology deployment in smart cities. Most cities cope with a proliferation of minor technology products and applications, mostly focused on a specific goal

Although there is no straightforward definition of a smart city, and it still remains a fuzzy concept (Witte & Geertman, 2017), the key domains in which cities can develop their smartness and which they can use to build more sustainable, resilient and responsive cities are economy, people, governance, mobility, environment and living, as pointed out by Giffinger et al. (2007). In almost all of these areas, the role of spatial information is present and geospatial components combined with other and new technologies can be used as a framework to support actions in these domains.

In general, a 3D virtual city model as is proposed in this thesis provides a framework that contains information that ensures a city operates smoothly and orderly (Li et al., 2013). This is done by organizing data via unified coordinate systems, making information spatial. This information can then be visualized, interpreted, analyzed in maps or 3D virtual models. This helps stakeholders in smart city development to recognize patterns and discuss natural, social and economic information related to the physical city.

Relevant data can for instance be visualized, organized, analyzed and interpreted by using interactive web maps. These web maps, as prime example of a geospatial application in smart cities, can be used to enhance stakeholder collaboration (governments, institutions, companies, citizens). They provide insight for discussing, interacting and decision-making.

To produce such a web map a number of steps have to be taken. This thesis has proposed a method for taking the initial steps by using geospatial technologies. It also argues that using these technologies and basing smart city development on spatial information is an important, if not the first, step to better make use of all the data that exists in cities. These data are usually locked away in spreadsheets, pdf's and other documents and are hardly accessible.

Potential use of 3D city models

For smart city applications such as the continuous monitoring of energy consumption, noise pollution and other issues, urban planners and policy makers could benefit from 3D city models. However, so far the use these models is confined to visualization mainly, which leaves other potential applications underexploited. The major challenge therefore is, is to find a way to create and use technologies that make use of geodata and 3D city modelling tools that are affordable, understandable, and easy to implement. 3D geometries can be (re-)constructed and non-spatial data can be integrated. This will hopefully result in a much better understanding of urban issues and ecosystems, thus resulting in more livable, sustainable and safer cities.

Recommendations

Finally, some recommendations can be made. As was discussed earlier, the smart city concept has attracted interest from a large variety of academic disciplines. Hence, many research challenges have been defined. These include challenges concerning city traffic, citizen behavior and city planning (Yin et al., 2015). This thesis underlined the complexity of making cities smarter and the challenges cities face. The same goes for academics researching smart cities. Whether it is their goal to theorize, analyze or design. Data collected in cities in different domains, using different technologies, can serve as a starting point. Research challenges can be very broad though because of the multidisciplinary characteristics smart cities have. ICT issues, social issues, environmental issues, economic issues, administrative issues, etc., are all included in smart city research. Some data-driven research issues can be related to city traffic, citizen behavior and city planning (Yin et al, 2015, p.12).

Apart from smart city research challenges, there is also a world to win with the further development of both the Virtual District Model and the Smart District Data Infrastructure. The VDM can for instance include other data sources such as open data from other platforms (e.g. Utrecht open data on Utrecht.dataplatform.nl). Also, it can be modelled in such a way that it allows for spatio-temporal simulations. Also, a next step could be to design a way of integrating different scenarios in the CityGML model. For instance, when multiple future scenarios co-exist and a choice has to be made between them. Each scenario might provide another model and have different consequences. CityGML offers the CityObjectGroup module, which can serve for this matter. Each scenario may include different modules on itself. Many other goals can be formed for future design work.

Next to the further development of the VDM, the SDDI can be further developed. As was discussed earlier, this framework as a whole is not yet in place but may provide a holistic approach to smart city/district development. When integrating sensors, BIM models, stakeholder data and provide applications, multiple functionalities can be added. A collaborative map can be designed for instance, consisting of a web application where citizens will be encourage to use the information provided by other partners and stakeholders and where they themselves can provide information.

These are again some examples of the potential of 3D city models and spatial information frameworks. The greatest recommendation can be to fully exploit the power an information system as is proposed in this thesis.

Concluding finally, in the present and upcoming years, cities that wish to be smart have a substantial growth opportunity for information management that is needed for smart city policies. This thesis argues that spatial information should have a major part in these policies. The role of geospatial technologies and GIS systems in smart cities can be to integrate multiple aspects of smart city planning and technologies, for instance data acquired by sensors in real time. This should help to make better decisions, improve efficiency and collaboration. Geospatial or location data must be recognized as a key ingredient of smart city development. Already smart cities can become much smarter with semantically enriched virtual 3D city models as is proposed by the prototype model.

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