DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

LEVEL OF DETAIL OPTIMIZATION FOR 3D CITY MODELS

by

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İZMİR

LEVEL OF DETAIL OPTIMIZATION FOR 3D CITY MODELS

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İZMİR

M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"LEVEL OF DETAIL OPTIMIZATION FOR 3D CITY MODELS"** completed by **BARKIN EMİRHAN GÜLER** under supervision of **Prof. Dr. Muhammed AYDOĞAN** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of.Master of Science.

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ABSTRACT

In addition to city planning, visual digital data and 3D models collected from the urban environment are an important source of inspiration for the field of urban design. As a contrast, the urban environments, rendered in traditional 3D city models, are highly representative and data-driven way. Equivalent to how the development of digital urban data (digitization) has created technologies such as computer-aided design (CAD), building information models (BIM), and geographic information systems (GIS), and made them the industry standard in the past; Industry 4.0; Advancements in 3D scanning technologies that provide realistic visualization of urban space; Increased capacities of graphics processors; The Digital Twin (DT) concept which combined with game engines, brings new perspectives to urban planning and design applications. In this study, besides the basics of a hypothetical LOD categorization to be built especially for the urban area, the qualitative connection between the LOD system optimization used in the field of graphics technologies and the 3D scanned models of the urban area has been examined.

Keywords: Digitalization, 3D Urban Models, Photogrammetry, Digital Twins, LOD, Urban Design

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ÖZ

Kentsel tasarım alanı, şehir planlarına ek olarak, kent mekanından elde edilen görsel dijital veriden ve 3D modellerden büyük ölçüde beslenmektedir. Buna karşın geleneksel 3D kent modellerinde kent mekanı oldukça temsili ve niceliksel veriye odaklı olarak üretilmektedir. Dijital kent verisinin gelişiminin geçmişte bilgisayar destekli tasarım (CAD), Bina bilgi modelleri (BIM) ve coğrafi bilgi sistemleri (GIS) gibi teknolojileri endüstri standardı haline getirmesine benzer şekilde; Endüstri 4.0; Kent mekanına ait gerçekçi görselleştirme imkanı sağlayan 3D tarama teknolojilerindeki gelişmeler; Grafik işlemcilerinin artan kapasiteleri; Oyun motorları ile birleşen Dijital Twin (DT) konsepti, şehir planlama ve tasarım pratiklerine yeni perspektifler kazandırmaktadır. Bu çalışmada, grafik teknolojileri alanında kullanılan LOD sistem optimizasyonu ve kent mekanını konu alan 3D tarama modelleri arasındaki niteliksel ilişki, ve kent mekanı özelinde oluşturulmak üzere hipotatik bir LOD kategorizasyonunun temel hatları araştırılmaktadır.

Anahtar kelimeler: Dijitalizasyon, 3D Kent Modelleri, Photogrammetry Dijital İkizler, LOD, Urban Design

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CHAPTER ONE

INTRODUCTION

1.1 Introduction

Creating accurate models of architectural objects and environments is considered an important element of the design process at almost every step. Understanding the surrounding and urban concepts is necessary to create a design that not only respects the location but is also well adjusted to its needs. Moreover, the creation of accurate models can be useful for urban and architectural analysis that can be performed within a 3-dimensional environment. Precise environment models are also crucial for all the automated analysis and design processes that can be applied due to the recent development of digital technologies in architectural and urban design.

The application of photogrammetric technologies can significantly impact such a process not only in terms of precision but also shorten the entire data gathering process and give all the needed information such as size, color, material, human scale, visual experience of space perception, etc., which is significantly valuable for the urban designers in the surveying stage of the design process. The development of technologies such as CAD, GIS, and BIM has led architectural and urban design to complete digitalization that has to be supported with customized tools. However, they are offering a limited visual experience, and it needs to be advanced or replaced with new generation developments for achieving a holistic tool using recent technologies in the fields of architecture, engineering, and city planning.

Creating digital copies of urban space with the help of scanning techniques is a relatively old technology. However, its use has been limited to the fields of architecture, engineering, and city planning. The use of the photogrammetry method in the digital game industry has facilitated the use of this technology and created a new perspective on the 3D digitization of physical space. The combination of high-detailed models with real-time rendering game engines has created a wide and open field for concepts like digital twins. Developments like this are leading us to think about the requirements of the next generation of tools to use in architecture, engineering, and city planning.

Based on the concept of the city digital twin, it can be thought of as a real-time convergence of two existing applications popular in the fields of urban planning and architecture. These concepts are BIM systems and CityGML applications. The creation of the two concepts serves quite different purposes, and although they have different software infrastructures, they both make use of 3D data and the categorization of this data over the concept of LOD (level of detail), which has emerged in the field of digital graphics. In BIM systems, this optimization is known as LoD (level of development) categorization, and in CityGML applications, it is known as LOD (level of detail) categorization. These categorizations aim to increase or decrease the amount of information it contains according to the scale of the observed 3D model and to balance the load on the processor of the system used. In this way, while the system processes and displays larger-scale 3D data, it processes less information associated with this model, and vice versa, the information and detail processed on the model at smaller scales can be increased.

The issue of creating a 3D scanned representation model and using it effectively in the design process requires several digital optimization interventions. A large system, such as a digital twin of a city or a part of it, requires very large amounts of 3D data to process. For this reason, it should also be considered a graphic optimization problem using a model with a specific LOD (level of detail) that is suitable for the selected design scale, to be created and used. Traditional 3D models (DCC) consist of units called vertex or face (mesh) and raster files. Viewing and editing the 3D models that make up the digital representation model using hardware becomes more difficult depending on the level of detail contained in the model, in direct proportion to the poly count and file size. As a contrast, photogrammetric models have different scales and sizes, as well as detail levels specific to their scales that have no definite boundaries and often include high geometry. Models created on the scale of the city texture with the photogrammetry method - depending on the requirements of scanning techniques - are created to include less human scaled detail as the scale grows. While displaying these models from a human scaled perspective, deformations in the streets and buildings become more visible, and the perception of realism is lost. However, a holistic city sized model that includes the human scaled details on the street-structure will reach dimensions that cannot be displayed with the processing power of the computer hardware used in the architectural field, as it will contain a very large file size and require rendering time. Optimization points can be found by using the correlation between the LOD (level of detail), observation distance, and number of faces to reach the representation of urban space at all scales, which will work in the most optimized way.

The aims of the study are to draw a technical LOD workflow that can be implemented on conventional LOD categorizations used in urban representation 3D models to display the characteristics of scanned models at every scale and to investigate whether the LOD optimization method in the digital graphic field, is useful for the models that take the urban area as the subject.

CHAPTER TWO

THEORATICAL FRAMEWORK

2.1 Digitization and Digitalization

Digitization and digitalization are two distinct concepts that are often used interchangeably, but they refer to different processes. The process of transferring analog information into a digital representation is referred to as "digitalization". Digitization is the conversion of analog information into a digital format of zeros and ones so that computers can retain, process, and transmit such information. Digitization also refers to the process of capturing, encoding, and storing analog data, such as audio, video, images, or text, into a digital form that can be manipulated, processed, and transmitted using computer technology. It is the transformation of analog to digital tasks (Verhoef et al., 2021).

The term "digitalization," on the other hand, refers to the incorporation of digital technology into all aspects of society and the economy. It was first used in German politics, but as seen by the rapid rise in publications, it also gained popularity in industry and academia. Digitalization is a different phrase used to describe current technological advancements (Lasi, Fettke, Kemper, Feld, & Hoffmann, 2014). This process involves the use of digital technology to automate, optimize, and transform traditional business processes, products, and services. Digitalization influences a wide range of activities, including e-commerce, big data analytics, cloud computing, and the Internet of Things (IoT), which has a significant impact on how organizations run as well as how people live and work.

The IGI Global Dictionary (2017) states that there are two definitions of digitalization, which include societal and technical perspectives. The societal perspective is that digital technology has been integrated into daily life. Making anything digitisable and implementing data in digital form are both instances that use the term "digitalization." On the other hand, the technical viewpoint related to information digitalization technology Computers are capable of processing digitalized information, which is often made up of binary numbers. The computer processes the numbers and provides information that can be read by humans (van Winden & de Carvalho, 2017).

A tool for creating innovative businesses and services is provided by digitization (Härting, Reichstein, & Sandkuhl, 2018). With the support of digitalization assignments, industrial processes may become more flexible and productive, which boosts their effectiveness and results in cost and energy savings. Additionally, the movement toward sustainable manufacturing and renewable resources can possibly be contributed to by digitization (Hofmann et al., 2022). According to the European Commission, "digitalization" refers to the transformation of a business or industry via the use of digital technology to enhance its operation (European Climate, Alpagut, Zhang, Gabaldon, & Hernandez, 2022).

2.2 Digitalization of Urban Data

Geospatial data was mostly created by national government entities in the previous ten years since it was so expensive to gather, compile, and disseminate it. In addition to making sure that the data was correct for as long as feasible, it was necessary to distribute the expense among as many applications as possible. Today, these concerns are mainly irrelevant, though, as production costs are now a small portion of what they previously were and anyone—even regular people—can acquire and produce geographic data sets (Turner, 2006). We are in the phase of the "4th Industrial Revolution," which is leading to an era of "digital abundance" after a period of relative data scarcity. The global scale of investments and attempts to create "smart cities" has served as the model for better cities in the digital age (Wan, Nochta, & Schooling, 2019).

Urban digitalization describes the process of changing the entity structure of urban development modes led by digital technology applications and data components, including the digital transformation of economic development, social life, government governance, and other components (Vial, 2019). Due to the growth of data-driven innovations, cities are aggressively using new digital technology to accelerate digitalization (Bokolo, Petersen, & Helfert, 2022). A city's spatiotemporal data may be modeled and viewed through a virtual representation (Mohammadi & Taylor, n.d.).

Additionally, a lot of factors, such as how areas are judged and classified and the quality of housing, are somewhat subjective and, as a result, cannot be replicated scientifically. As a result, it is possible for two observers to arrive at different conclusions when asked to make the same evaluation. Since the words correctness and error require agreement on the presence of a true value for such variables, uncertainty is now preferred when talking about its function in geographic information science (Goodchild, 2022). The importance of urban simulation for the general public was emphasized by Boffi and Rainisio because it frequently takes part in urban regeneration activities that are directly related to social issues in modern cities. The need for an interdisciplinary approach is emphasized, and it is suggested that the simulations be thought of as urban cultural objects that might foster social interaction and communal well-being (Boffi & Rainisio, 2017).

Early in the design process, data is gathered and analyzed by urban designers for two reasons: first, to examine previous projects as models, and second, to gain a better understanding of the site's characteristics. Conducting environmental analysis on the gathered data is part of interpretation. The study's findings are referred to while doing performance-based urban design. Environmental analysis needs 3D city data, which is rarely accessible in 2D city data (Biljecki, Stoter, Ledoux, Zlatanova, & Çöltekin, 2015). 3D city models appear to have been mostly utilized for visualization throughout the last few decades, but they are now increasingly being used in a variety of fields and for a wide range of purposes other than visualization (Biljecki, Stoter, et al., 2015).

2.3 Conventional Methods of Processing 3D Urban Data (CAD,BIM,GIS)

The advancement of computers significantly changed how technical drawings were designed and produced (Bertoline, Wiebe, Hartman, & Ross, 2008). It involves the use of computer software to create drawings. Today, the range of design processes accessible to architects, which may impact modern architectural styles and the manufacture of architecture and its components, is greater than ever due to the development of various Computer-Aided design (CAD) and additional software programs (Dunn, 2012).

Since the early 1960s, when it was used to describe the fundamentals guiding the design of computer operating systems and hardware, the term "architectures" or "computer architecture" has been used in the IT industry (Anthony Jnr, 2021). The development of computer-aided design (CAD) software in the middle of the 20th century represented the beginning of the digitization of urban data. Although CAD provided the capacity to digitally represent the associative geometric relationships, it was still only capable of creating a static representation. We can now describe behavior beyond geometry and develop dynamic models that can incorporate real-life scenarios thanks to the capacity to merge data into the digital prototype (Francisco, Truong, Khosrowpour, Taylor, & Mohammadi, 2018; Ju et al., 2021; McCall, 2021).

To understand a condition and identify design possibilities and solutions for spatial challenges, urban planners and designers rely on spatially linked information and knowledge. Numerous individuals are informed by the decisions that planners either make or assist others in making based on geographic location, spatial patterns, and the distribution of features or events throughout an urban environment. Urban planners have a platform to deal with these diverse spatial contexts and describe, evaluate, and model them by using geographic information systems (GIS). Through extensive geographical analysis, it also produces fresh insights and contributes to the planning process's effectiveness and adaptability (Aydinoglu & Bovkir, 2020). Geographic information systems (GIS) are widely considered a technology that primarily focuses on utilizing geospatial data by allowing simultaneous access and processing of numerous different data types based on a common location, or, in other words, to compile numerous pieces of information about a location and its surroundings. These data types are probably conceived of as layers in the geospatial domain, a term that dates back to early GIS and is mostly derived from maps (Goodchild, 2022).

Today, real-time visualization in a variety of sectors, such as urban planning, city planning, and architectural design, is effectively achieved using VRGIS (virtual reality-based geographic information systems) (Beck, Ag, & Zurich, 2023).

The projection of horizontal features on digital map data, occasionally mixed with image matching methods using aerial photograph data, is an example of how GIS software and 3D visualization are merged. This is more optimal for simulations and analyses of broad geographic areas (Shiode, 2000).

A key component of the most recent digital revolutions in the architecture, engineering, and construction (AEC) industry is building information modeling (BIM) (Oyesode, Dare-Abel, & Daramola, 2022). BIM, as defined by Sacks et al., is a general term for advanced 3D Computer Aided Design (CAD) technology for modeling and managing buildings and information related to them. BIM models differ from conventional CAD platforms in that the objects in a BIM model are understandable to computer programs as depictions of real-world building components, as opposed to the graphic items in a two dimensional CAD file. (Sacks, Koskela, Dave, & Owen, 2010). According to Aliabadi and Mirsharafi, theoretical advancements in building information modeling (BIM) indicate that it can help with project management (PM) and sustainable design architecture in addition to the geometric modeling of a building's execution. Both BIM and sustainable design are altering how architects view their work (Aliabadi & Mirsharafi, 2013).

The utilization of undetailed GIS and CAD style 3D models, also known as clay models, in urban planning and design fields has been a controversial issue. While these models provide a simple and efficient way of symbolizing the city structures through their volumes, they lack the necessary detail to truly capture the urban character. This lack of detail in the 3D models can lead to incorrect representations of the city, ultimately affecting the decision-making process and resulting in poor urban planning and design outcomes. Moreover, the absence of urban character in the 3D models can hinder the understanding of the context, culture, and heritage of the city. On the other hand, detailed models that include the urban character provide a more comprehensive representation of the city, allowing for better decision-making and urban planning and design outcomes.

2.4 3D Data of the City

Global technological advances and developments are constantly met with strong opposition. A new technological advancement or system must overcome significant resistance. In regard to 3D information, this phenomenon is much more crucial. Not only is the transition to the third dimension technically difficult, but it also requires mental progression. The old 2D representation must be abandoned in favor of a real 3D representation and 3D reasoning of space due to conceptual progress in the geo-information area (Roland Billen, n.d.).

Since conventional geodata was previously only available in 2D and 2.5D, 3D city models naturally began with 3D building models. Buildings, particularly those that are modeled in more depth, cannot be depicted in 2D or 2.5D; therefore, this has a technical element (Lehner & Dorffner, 2020).

Combining them with 2D (i.e., city map) and 2.5D (i.e., digital terrain model) GIS data sets is a typical method for producing a 3D city model that includes more than just the buildings. The city map is often utilized as a raster image on the terrain model when the models are simply used for display (Lehner & Dorffner, 2020).

Problems are typically brought on by the data sets' time-related disarray. While it may be possible to ignore these issues while creating a 3D city model for display reasons, they must be resolved if the model is to be the foundation for a city information model (Lehner & Dorffner, 2020).

Ying claims that urban growth and densification processes transform cities, especially in the third dimension (3D), necessitating a technical switch from 2D to 3D for assessing the dense urban structure (Ying, Koeva, Kuffer, & Zevenbergen, 2023).

With a variety of techniques and accuracy, the actual world may be realistically digitally recreated in three dimensions. Despite the fact that these techniques might be regarded as an older technology, they have advanced quickly thanks to 3D software. In the domains of architecture and urbanism, this growth has driven trends in the digitization and storage of physical data. These approaches were in line with the methodologies' demands for economic viability and efficiency.

Although there are additional techniques exclusive to the engineering and military sectors used to create 3D city scanning models, photogrammetry and lidar are the two most often employed techniques.

LiDAR (Light Detection and Ranging) scanning, using both airborne and terrestrial sensors, allows for the definition of the shape of an object or landscape by measuring the time interval between the emission of a laser pulse and the capture of its reflected signal on the component being measured (Jelalian, 1991). Some sensors can achieve sub-center precision with sub-meter accuracy. The biggest advantage of LiDAR over conventional image sensors is the collection of excellent quality three-dimensional information, allowing one to extract highly precise dimensions of objects and structures of interest as well as identify anomalies and flaws. They are also active sensors that are unaffected by ambient light, giving them a very precise source of data with less noise than other technologies. LiDAR is a very intriguing tool for defining the geometry of several territorial and urban components as a result of this circumstance. This acquisition productivity, however, contrasts with how difficult information is to process because it requires a significant investment in computational resources and technological know-how. As a result, increasing A large amount of research is concentrating on creating effective algorithms to assess LiDAR data (Fernández-Arango, Varela-García, González-Aguilera, & Lagüela-López, 2022). Currently, laser scanning methods are popular, but they also have significant disadvantages, such as high equipment costs, large amounts of point cloud data, and editing requirements. Another crucial element is managing and storing (Singh, Jain, & Mandla, 2013).

Several pictures of the same scene or object taken from various perspectives and angles must be analyzed using photogrammetry software. There are various ways to get information for photogrammetry. To represent a region in its entirety, several high-resolution aerial photos are taken. Any location on the ground is visible in numerous shots from various angles thanks to the overlap of these images. The several perspectives of the picture data are used by photogrammetry software to produce accurate 3D maps. With post-processing in place, exact GNSS locations are captured for every pixel of every picture, providing absolute precision in the final map down to the cm-level. Long after aerial photogrammetric capturing methods were developed, the idea of oblique image capture was introduced in the literature. The oblique image gathering approach is used to model building edge surfaces that are impossible to get using vertical (nadir) image acquisition and to solve issues with high-rise building orthorectification in metropolitan environments. Unmanned aerial vehicles (UAVs) are thought to be capable of acquiring oblique images without the need for aerial photogrammetry using special flight plans (Karasaka & Makineci, 2021).

2.5 New Generation Tools

As information technology has developed, a broad range of new digital tools have become available that may support the general operations of spatial analysis and urban modeling. Particularly in the context of spatial decision-making and design, these tools provide support at different phases of the process, including storing and retrieving data that is quick and efficient, survey and analysis that makes use of a variety of visualizations, and information dissemination to the community that will be impacted (Delaney, 2000). Within the next 10 years, remote access to data and software, as well as real-time content development over a network, are anticipated to become standard. This will pave the way for completely new methods in which users may engage with these models and in which the general public can take part (Shiode, 2000).

It is also noteworthy that orthophotos and LIDAR-style technologies are now used to capture height data. The majority of the models we looked at no longer measure and record height information manually. The creation of such models is currently thought to require various forms of photogrammetry, and here is where the path to automation of the entire process lies (Shiode, 2000). However, this data is often too large and complex for traditional urban planning and design tools to handle effectively. As a result, there is a growing need for new generation urban planning and design tools that can handle these data sources and use them to inform decision-making processes.

The creation of 3D models today requires two things: remote sensing technology and spatial information databases. These two elements could soon become fundamental components of 3D models due to the increasing rate of adoption of information technology. As a result, a real-time, automated modeling technology will develop that will enable us to automatically construct a model on-site, wherever the remote sensing data are obtained, by downloading them into industry-standard programs that produce efficient and usable models. Following the emergence of geographic information technologies, these technological advances in modeling features appear to be only a matter of time. The key question will be how far this automation will extend to custom applications, especially those that address professionally related issues. Specialist and particular modifications of broad concepts are expected to continue to be the norm in this regard. But it's conceivable that programs will develop that can produce high-quality, accepted models (Shiode, 2000).

To ensure that the built environment is produced in a sustainable, equitable, and livable manner, big data must be included in urban planning and design processes. To accomplish this, next generation big data-capable urban planning and design technologies must be created. Academic circles generally agree that digital twin applications in the urban sphere are one of the most promising ideas.

2.6 Digital Twin Concept

A digital twin is a digital version of a real entity (Wan et al., 2019). Digital twins are a growing idea that involves digitizing the components, procedures, and systems of physical things in order to provide interactive simulation models that may be used by a variety of professions (Lehner & Dorffner, 2020). Multiple current developments in digital information systems played a role in bringing digital twins to the agenda. Luo claims that "digital twins" combine the internet of things (IoT), machine learning, artificial intelligence, and data analytics to produce dynamic, live digital simulations of real-world objects (Luo, Hu, Zhang, & Wei, 2019). Digital twins are becoming more common as a result of the availability of tools that enable digital twin data, services, modeling, and connectivity to the real world (El Saddik, 2018). These technologies, which are created primarily for use in the management of industrial ecosystems, enable the testing of the final product at every stage of the design process to guarantee that it is practical, secure, effective, and dependable (Rosen vd,2015). As a consequence, in recent years, the idea of a digital twin has also drawn attention as a subject of conversation about the smart city (Batty, 2018). Urban digital twins are presented as an integrated and effective method for managing data-based infrastructure and undertaking urban sustainability initiatives (Park, Lee, Park, & Park, 2019).

Rapid change is occurring in the architectural, engineering, construction, and operation (AECO) sector. The future of the sector is being shaped, in particular, by technological developments and the lessons learned during the COVID-19 epidemic. By allowing more self-reliable, self-automated, autonomous, practical, and cost-effective processes throughout the various stages and phases of a smart building or city, various artificial intelligence (AI), building information modeling (BIM), and Internet of Things (IoT) techniques have helped to modernize the industry. The idea of digital twins (DTs) has consequently come to light as a viable remedy to improve the AECO sector in order to accomplish the necessary cyber-physical cooperation, especially in the wake of the pandemic (Megahed & Hassan, 2022). Urban population density is expanding quickly, necessitating a continuous demand for additional infrastructure and services for residents. Plans and policies of local authorities and stakeholders would benefit from passing through a number of virtual stress tests in order to shorten the time to execution and optimize the financial cost of alternative solutions. Prescriptive and predictive technologies are frequently used to achieve this goal, improve city planning, and comprehend urban processes and environments. However, comprehensive sandboxes that are closely connected with cities are still generally absent. The city digital twin is an innovative idea that offers a tool for testing out new ideas in a safe setting before implementing them (Hristov, Petrova-Antonova, Ilieva, & Rizov, 2022). Without having to conduct expensive or impractical physical experiments, the well designed virtual system enables analysts, planners, and engineers to draw valid conclusions about the city (Ketzler et al., 2020).

Digital twins are exact virtual replicas of real objects that reflect reality using networked digital data from satellites, drones, sensors for geographic information, and other sources. When it comes to cities, planners and engineers may use digital twins to learn more about how to improve services, plan projects, optimize the systems in buildings, and keep an eye on traffic flow. Before they are built, designers may replicate concepts in a real-world urban setting and assess the effects of choices like where to place a bus stop or the size of a new housing complex (McCall, n.d.).

It is possible to think of a world in which the effects of the enormous increases in atmospheric greenhouse gases could have been replicated in a laboratory rather than being the focus of the massive experiment on the environment that has been ongoing since the beginning of the industrial revolution. In theory, a digital twin allows processes that have an effect on the real world to be simulated on a digital copy. Recently, there has also been a lot of discussion on the idea of a digital earth, or a twin of the world in cyberspace (Guo, Goodchild, & Annoni, 2020). While there is a consensus that digital twins will be beneficial in the field of long-term efficiency and sustainability, another issue that has been widely discussed is that they can provide a wide simulation environment for rapid decisions by city managers and planners in events that affect large audiences. According to Ford and Wolf, urban planners permit the use of digital twins to assess the effects of various city scenarios, such as planned development projects and catastrophe management: By offering decision-makers accurate predictions of the likely effects of suggested actions through quick and low-cost testing, digital twins can also enhance and perhaps optimize disaster management systems. However, as will be shown, digital twins have not yet advanced enough to fully realize these advantages, and more effort is needed to construct digital twins at the community level for better emergency management or general community management (Ford & Wolf, 2020). The digital twin is a virtual representation of the real city that gathers information on its processes, infrastructure, and services using both readily accessible technologies and specially constructed linked gadgets and sensors. In this context, the creation of urban living laboratories makes it easier to monitor and comprehend urban activities and enhances the digital twin with data that is very pertinent (Hristov et al., 2022).

A digital twin includes: a physical object that produces real-time data on how it functions or utilizes sensors to collect real-time data about what's going on around it; a 3D representation of the real thing; a constant and live data flow between the actual object and the 3D model; and a computer-based system that, utilizing the real-time data obtained, causes the 3D model to behave visually like the real thing (McCall, 2021).

The 3D digital environment should be a reflection of the real physical environment. On the other hand, traditional 3D city data existing in city plans and databases does not always correspond to real life. “A key characteristic of a digital twin is that it is connected to a physical entity, which is typically established by the use of real-time data using sensors.” (Atzori, Iera, & Morabito, 2010; Tekinerdogan & Köksal, 2018).

Time and the requirement for current data in many applications are two of the biggest gaps between data and the actual world. Some characteristics, such as the existence and placement of roadways and other physical infrastructure, change gradually (Goodchild, 2022). When the development has been kept in 3D digital format, it will create much useful, proven, and traceable knowledge of the city's spread, form, and direction, as well as important information for urban designers and planners.

Another key aspect, the information exchange between the physical and virtual worlds, is another crucial component of digital twins that makes it possible to accurately represent the physical counterpart (Ketzler et al., 2020). The public can explore a detailed 3D model of a city that has been released online to see suggested changes to urban planning and policy. Before putting these judgments into action, this makes public disclosure and transparency simpler. A further virtual feedback loop where residents may engage and provide comments on proposed changes to the city is made possible by this open and transparent architecture. Additionally, residents can engage with components to flag and report issues in their neighborhood (White, Zink, Codecà, & Clarke, 2021). A digital twin is a 3D replica of an actual object, such as a city or building. But with function, continuous data updates its operations in real-time, giving a way to assess and improve a structure. When the digital copy receives real-time data from the actual system, it behaves exactly like the original, providing you with immediate visual feedback on your operations. By analyzing and predicting efficiency, the gathered data may be utilized to compute metrics like speed, trajectory, and energy consumption (Ju et al., 2021).

In addition to the broad discussion of what digital twins are and how they can benefit, there are aspects that have not been adequately studied and agreed upon. Goodchild has brought some of the questions as, There will always be a degree of confusion about this concept because a digital twin cannot be an exact replica of a city or the Earth: What level of completion does a representation need to reach before a developer can call it a "digital twin"? What applications will a digital twin that isn't fully supported use, and what apps won't? How should the unavoidable error of a digital twin that isn't complete be quantified, represented, and communicated to affect its predictions? (Goodchild, 2022). Hence, accuracy and certainty should be understood in terms of specific use cases rather than as characteristics of data that need to be assessed and reported as an integral part of metadata. Given its inherent uncertainty, for what applications is data collection acceptable, and for what applications is it not? This is known as the notion of appropriateness for use, and it is only one of many ways that the conventional view of geographic data is being questioned (Turner, 2006). Digital twins have received a lot of interest in the urban and geospatial realms, according to Lei. While the advantages of creating urban digital twins have been widely recognized in decision-making, their difficulties are not frequently the focus of thorough debates (Lei, Janssen, Stoter, & Biljecki, 2023).

While the idea of the city-level digital twin is gaining traction in the UK with several noteworthy pilot projects under construction (e.g., Exeter, Bristol, Newcastle, Milton Keynes) or being considered (e.g., Cambridge), the different approaches and the less obvious policy results of these experiments imply a serious knowledge gap around the city-level digital twin in terms of what it is, what/whom it is for, and how to build/use/manage/regulate it to deliver better public services (Wan et al., 2019).

Ju et al. explain that digital twins have the potential to be an effective planning tool for smart cities. Virtual Singapore planning, SideWalks initiatives in Toronto, CityZenith planning of the Indian city of Amaravati, Glasgow's Future City program, or Cambridge University's National Digital Twin project are a few examples (Ju et al., 2021). According to an article published on The B1M, 51World used data from satellites, drones, and sensors to generate digital versions of numerous other buildings, roads, waterways, and green spaces. The company also individually modeled over 20 iconic structures, including the Oriental Pearl and Shanghai Tower. The ultimate goal is to develop this model into a real digital twin that is updated continually and almost instantly (McCall, n.d.).

2.7 Gaming Engines and Digital Twins

A tool with significant educational potential is gaming. They provide excellent opportunities to produce 3D visuals with hardware support in real time. They make it possible to manipulate objects around in a scene. The most advanced area of computer graphics is found in games, and the interaction of these products establishes the educational potential. A user is rewarded for employing practical abilities including memory retention, reasoning, creativity, and problem-solving (Hanzl & Wrona, 2004). In a number of fields, including architecture, cinema, aerospace, and automotive, game engines are already being used to provide a wide range of simulations, VR experiences, and real-time visualizations. The creation of digital twins is a logical next step for these businesses, given the existing 3D models (McCall, 2021). Urban digital twin systems also started to have a wider usage than they did before when they were merged with real-time visualization and operation opportunities, such as a widely used gaming engine like Unreal Engine. According to Unreal Engine developers, the distinction in this case is made by real-time computing. The setup and upkeep of a digital twin are simpler and quicker using a gaming engine than they are with custom programming. Like any well-designed game would be, the outcome is also simple for everyone to use and operate (McCall, 2021).

Developing tools that are possible with real-time visualization engines can make analysis and observations measurable in the fields of architecture and urban design. The DTCC team examines sound data as one sort of data. According to Fabio Latino, Design Lead at the DTCC, "Since sound is invisible to the human eye, these visualizations can help users understand potential problems concerning the sound environment, which can be applied by planners in urban planning processes." An effective technique for replicating and visualizing an intangible energy like sound is a game engine like Unreal Engine. For the AECO sector, this capacity has fascinating applications (Pimentel, 2021).

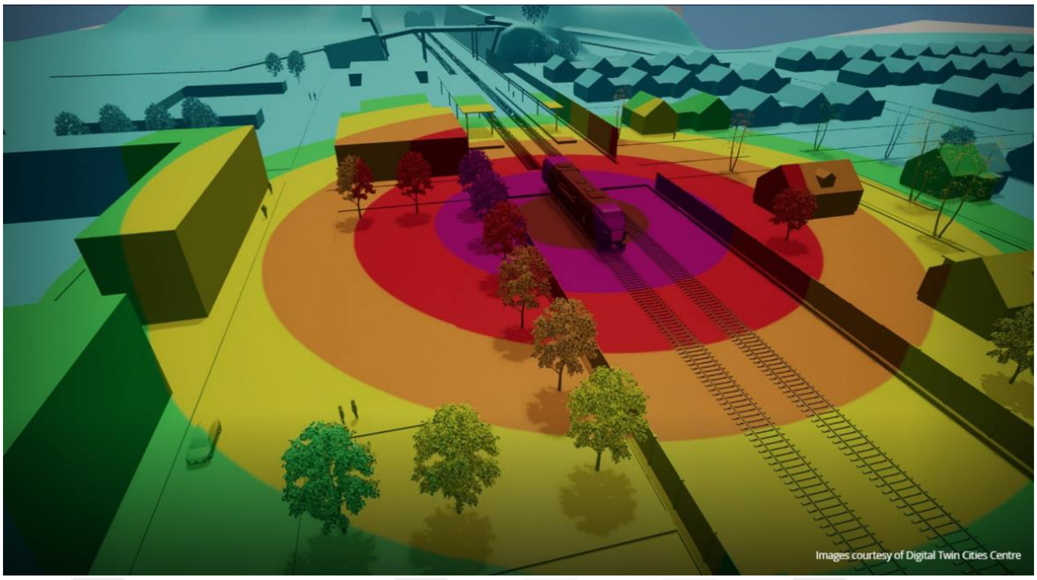


Figure 2.1 Sound Analysis In Digital Twin

We've had the tools to build digital twins for a while. But until quite recently, there was a high entry barrier for digital twins; for initial setup, a skilled developer was needed, and subsequently, a User Experience (UX) designer was necessary to make the digital twin usable by non-technical staff. However, building and maintaining a digital twin required a lot of time and work (McCall, 2021).

In addition, the problems to be overcome are not limited to the tools. As with any engine-based project, there are optimization limits with which to be concerned. The whole simulation is split into two-square-kilometer pieces that are loaded and unloaded in accordance with the camera perspective in order to improve the photorealistic real-time rendering of the Shanghai model in Unreal Engine. Closer objects appear in more depth, with reliable reflections from the surroundings, gentle surface shadows, and realistic weather-shading effects. To mimic actual daylight, the team employed the Sun and Sky model in Unreal Engine (McCall, n.d.).

Unlike BIM or GIS systems, game engines use LOD optimization to effectively use the capacity of the graphics processor by organizing it with the distance factor in displaying 3D models, meaning in computer graphics. Unreal engine allows the use of 8 different LOD levels. The numerical connection of this categorization with 3D models is not standardized. This is because 3D models are a wide-ranging concept, and the number of surfaces is determined by the developers according to the needs of the scene. Although there is no standardization at the model level, the total number of surfaces that will take place in an unreal engine scene is determined over the fps values and is determined in direct relation to the system in which the targeted application is used. While it is not a standard agreed upon by Unreal Engine developers or its platform, it is common practice that "an unreal engine scene should have several million surfaces".

2.8 City Scale Digital Twins

An essential tool for digital twins would be creating an interoperable master database of the built environment using 3D geospatial modeling. However, this does not imply that a city's digital twin can only be useful if the entire metropolis is geometrically duplicated in the digital realm (Wan et al., 2019).

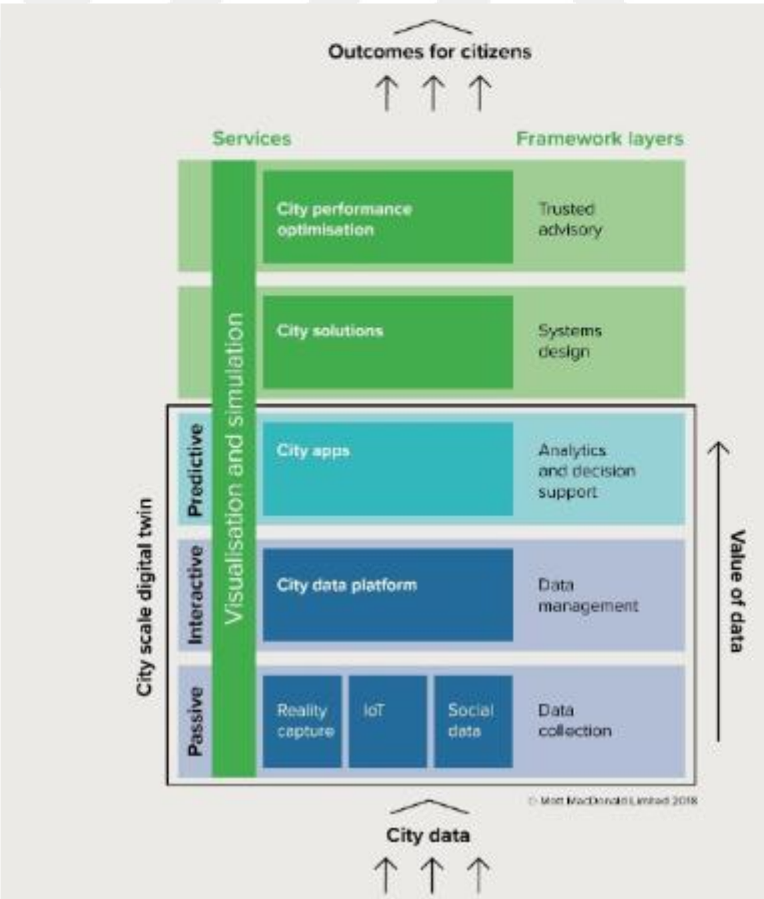


Figure 2.2 City Scale Digital Twin (Wan et al., 2019)

The data inputs, together with the corresponding level of detail and alteration, must be established according to the objective for a city-level digital twin to be effective and practical. Those requirements are not always fixed and can be changed later to account for any changes in purpose or advancements in technology (Wan et al., 2019).

In academia, Batty (2018) provides an insightful discussion over some fundamental questions about the digital twin concept. He argues that the digital twin, as an exact mirror of the physical system, represents a distinct approach compared with conventional urban system models, where abstraction remains a core element to enable realistic construction and operation of models. In addition, he argues that "a true digital twin operating in real time is no different from the system itself, which raises the issue of how the digital twin can be used to explore, simulate, and test new designs if it is the system itself (“Digital Twins - Michael Batty, 2018,” n.d.).

We believe that participatory procedures continue to be mostly conducted using 2D city representations, such as plans and planning ideas, in primarily technical and/or expert language. In the context of urban planning procedures, virtual, interactive models are still very uncommon. Therefore, knowledgeable groups can implicitly or explicitly compare these traditional forms to Herrenberg's urban digital twin model. In consideration of this supposition, it can be deduced that virtual models have the potential to enhance participatory processes due to the fact that users with prior experience evaluate the model more favorably than users without this expertise on five of the six aspects. This may be used, for instance, to help laypeople and specialists communicate more effectively by simplifying difficult material (Dembski, Wössner, Letzgus, Ruddat, & Yamu, 2020).

The city-level digital twin offers a valuable simulation environment for testing different policy alternatives, which is seldom achievable in the actual world and is helpful for municipal policy development (Wan et al., 2019).

With the help of this digital twin, we also aimed to illustrate a method for facilitating urban data and upholding data sovereignty, for instance, by cities and their residents. In contrast to Google, Cisco, IBM, and many other producers of urban data and smart city solutions, our goal is to protect the independence of smaller towns in particular rather than to develop a commercial product and the dependencies of cities on the providers of the data. In order to facilitate future research and provide planners and decision-makers with the opportunity to adopt and enhance these techniques, the project also strives to guarantee the approach of software and data availability by utilizing open source tools like COVISE, OpenCOVER, and OpenFOAM (Dembski et al., 2020).

The data inputs, together with the level of detail (LOD) and rate of change associated with them, must be established in accordance with the goal of a city-level digital twin to be effective and viable (Wan et al., 2019).

2.9 Concept and Conflicts of LOD

One of the fundamental terms used in GIS and 3D city modeling to define the complexity of the representation of a geographic entity is level of detail, which was first used by Clark (1976). LOD is a notion that was taken from computer graphics (Clark, 1976; Luebke et al., 2002). 3D information systems and architecture require the rich, photorealistic presentation of 3D data sets for an improved visual experience. Due to the extensive information connected with 3D objects, however, simple accessibility with effective rendering becomes challenging. Various applications thus require varying levels of detail (LoD) (Baig, 2013). A widely known computer graphics method for navigating through vast volumes of data is visualization utilizing several LODs. Only when the object is extremely close to the observer does the most thorough description of the object (i.e., the most data for processing) appear on the screen (Zlatanova, 2000).

Also, interactions between these 3D models are mostly possible when the large amount of data has been simplified. Compact storage and quick presentation of geometry data are essential in computer graphics and the closely connected disciplines of virtual reality, computer-aided geometric design, and scientific visualization. Real-time performance is a key objective for interactive applications like computer-aided design, video games, and military flight simulators. For these applications, the geometry may be broken down into many levels of complexity, and depending on the size of each object's screen, the display can move between the relevant levels of detail or mix between them (Nehab, Barczak, & Sander, 2006). LOD, one of the most well-known and fundamental optimization strategies, may be applied at either the beginning or the conclusion of the modeling process. Like every optimization approach, the LOD process has benefits and drawbacks based on the application stage. To put it another way, "reducing the number of polygons in a model may indicate the difference between slow display and real-time display (Nehab et al., 2006).

As it has become feasible in recent years to produce models with ever-increasing levels of detail, simplifying surfaces has become increasingly vital. Several fields produce intricate surface models. For instance, in computer vision, surface models made up of millions of polygons may be produced with ease utilizing range data obtained from scanners, such as photogrammetry (Nehab et al., 2006). Due to its size, complexity of structure, and topological finesse, modeling urban scenes is a difficult problem for the photogrammetry and computer vision communities (Han et al., 2021). Making a digital twin of the Hungarian State Opera building using 3D models presented a number of challenges, one of which was handling the enormous data sets. Some of the more complex rooms had 40 million data points, which had to be decreased to 3–4 million in order for the engineers to construct the bigger components of the building (Smisek, 2018).

Recently, two trends in the creation of 3D architectural models have become apparent. On the one hand, 3D structures are being designed in greater depth, raising the computational demands for visualization. For the visualization of spatial information, such as a street network with 3D buildings and transit facilities, little mobile display devices, such as cell phones and PDAs, are becoming increasingly crucial and well-liked (Fan & Meng, 2012). The visualization of buildings at various levels of detail (LoDs) is necessary for the effective display of 3D building models (Glander, T. and Döllner, J. 2009).

It is crucial to know which level of detail (LoD) makes it easier to create a precise neural map in order to make modeling and visualization decisions for a "walkthrough" experience in a virtual environment. Regulating the quantity of polygons used to make an item is perhaps the most popular method for regulating the LoD of a 3D model, which serves as the basis for all virtual environments. For instance, "distance to the viewer" is one of the most well-established spatial criteria; in this case, a 3D object's complexity (number of polygons) is purposefully reduced as it goes further away from the camera or viewer. As a standardized idea for determining degrees of complexity for portraying geographic elements in city models, LoD (Biljecki et al., 2013). These standardized LoD definitions are employed in 3D modeling as a way to describe product requirements (and to make purchasing easier) and as a first step towards generalization (Rautenbach, Coltekin, & Coetzee, 2015). According to published research, utilizing or understanding 3D models that are improperly constructed can lead to feelings of tension, irritation, stress, and confusion (Cubukcu, 2011).

The LoD specification in CityGML by the Open Geospatial Consortium (OGC) is applied. Five sequential LoDs for urban models are differentiated according to the CityGML standard, each with a higher level of complexity and specificity in terms of both their geometric representation and their thematic distinction (Groger, Kolbe, Czerwinski, & Nagel, 2008).

LoD0: The lowest level is called LoD0, which is regional and landscape. It is simply a 2.5D digital terrain model that can be overlaid with aerial photography to produce a more realistic impression.

LoD1: The first level is made up of well-known block types with prismatic buildings that have no (or flat) roofs.

LoD2: The level now has distinct roof constructions and surfaces with distinct themes.

LoD3: Exterior architectural models, landmarks: Architectural models of level three include intricate wall and roof structures, balconies, and bays, to mention a few.

The outside design of the structures should, at this level, correspond to the actual thing. A LoD3 model also includes finely detailed landscape and transit features.

LoD4: The fourth level of interior architectural models adds details to the inside of the structure, such as the number of rooms, inner doors, stairs, and furnishings. (Rautenbach et al., 2015)

The CityGML LoD definition has drawn criticism. (Biljecki, Zhao, Stoter, & Ledoux, 2013; Fan & Meng, 2012); Yet, this definition will be utilized as the primary distinction between the various degrees of visual complexity employed in this experiment, as it is the only one that is currently defined by either the International Organization for Standardization (ISO) or the Open Geospatial Consortium (OGC) (Rautenbach et al., 2015).

The level of detail (LOD) is a metric that describes the scale and quality of 3D city models (Biljecki, Ledoux, Stoter, & Zhao, 2014; Coltekin & Reichenbacher, 2011). Certain scenarios need datasets with a specific minimum LOD in order to be usable, and the LOD suggests the intended scope of use of 3D geoinformation (Biljecki, Heuvelink, Ledoux, & Stoter, 2015; Ohori, Ledoux, Biljecki, & Stoter, 2015; Strzalka, Monien, Koukofikis, & Eicker, 2015). Nevertheless, according to (R. Billen et al., 2014), this categorization is a bad concept for the following reasons. The LOD that was utilized in the study or the lowest LOD that would be necessary are frequently not emphasized in studies (Zhu, Hu, Zhang, & Du, 2009); We have come across use cases where LODs are utilized with both simple block models and architecturally detailed models that incorporate interior (for example, to determine the volumetric visibility), illustrating how the specified applications of LODs may be rather diverse; and (Döllner, Baumann, & Buchholz, 2007) Rarely is the performance of use cases LOD-wise examined (Biljecki vd., 2017; Biljecki, Stoter, vd., 2015).

CHAPTER THREE

METHOD

3.1 General Research Method

A LOD decision-making workflow is described in this study for optimal creation of a digital representation of an urban area using the most common remote sensors available for modern computers in AEC companies.

The first step in the methodology of this study is the selection of equipment, such as remote sensing methods, to be used. Software and capture tools are selected to use the chosen approach to generate the models. Therefore, a modeling study was carried out on the campus of the Gdansk Politechnika University using various scaled objects and technology. During the research, open source software and 3D models were selected and used as much as possible.

In the second stage of the study, 3D open source models were selected and created using remote sensing techniques. Ten unique 3D cityscape models of various shapes and sizes were selected to be evaluated for the primary study. The research also explores the best way to relate scales in urban design, using scale models for both architecture and urban planning. Based on the technical features of the models and the statistical data obtained from the selected models, interpretations were produced.

In the last part of the study, ideal LOD optimization levels were used, and suggestions were made within the limitations of the study.

3.2 Defining of Tools

In recent years, we have seen a tremendous increase in the use of photogrammetry, especially in urban planning. It differs from other remote sensing techniques, including lidar and GIS-based systems, in that it can effectively record the subtle features and textures of an urban environment. Urban designers, planners, architects, and politicians can examine the built environment and make decisions more easily using 3D models produced with photogrammetry.

Lidar technology, unlike photogrammetry, is costly and only works with specialized tools and personnel. In contrast, photogrammetry is a more practical and cost-effective approach for urban modeling as it can be performed with normal cameras and drones. The main benefit of using photogrammetry for this research is that it is more economical than other remote sensing techniques.

GIS-based solutions are limited to vector-based representations and generally do not include textures. Urban designers, planners, and architects can take advantage of photogrammetry to get a more realistic and immersive experience that will enable them to make better decisions. These benefits led to the selection of photogrammetry and remote sensing technology as the primary tools for the study.

3.3 Obtaining Data From Selected Methods With Different Tools and Scales

3.3.1 Basic Camera Settings and Types for Photogrammetry

The selected camera type and camera model, as well as the angle and distance of the photograph, directly affect the quality and size of the city representation models produced by the photogrammetry method. This correlation is proportional to the resolution, focal length, and number of megapixels of the camera. For photogrammetry, cameras with 18 - 20 megapixels and above, a wide focal length range such as f8 - f11, high resolution values such as 2K and 4K are preferred.

These settings can be used with a wide variety of commonly used cameras, including phone cameras, drone cameras, and DSLR cameras. However, the needed photography has shifted to aerial photographs rather than ground-level photographs that can be taken when the dimensions of the area to be scanned change from object size to city scale. Depending on the type of metropolitan environment, scanning the area requires an extremely precise shot path and number. This is why small metropolitan areas may only need drones weighing between 4 and 25 kg and their camera equipment, while as the region expands, larger cameras and larger types of drones and aircrafts are used.

3.3.2 Scanning of a Different Sized Object

In order to better understand this relationship and to choose the scanning method to be used within the scope of the study, different urban furniture and structures on the Gdansk Politechnika University Campus were scanned with cameras with different characteristics, and mesh models were created. These models were statistically analyzed and interpreted in terms of mesh surface numbers and detail levels.

Object_1 is a structure located on the campus of Politechnika University of Gdansk. The dimensions of this structure are approximately 40x40x100 cm in length, and it was created with a shooting route of approximately 600 cm in diameter and two different height levels.

Figure 3.1 Pictures of Object 1

The models obtained by DSLR camera, phone camera and drone shots, respectively, are as follows. Among the models created, the highest level of detail was obtained using a DSLR camera with a face number of 5,062,806. Although the model obtained with the phone camera is lower in terms of realism, with a face number of 1,049,348, it yielded results close to the detail level of the model created with a DSLR, with a surface number close to one-fifth. The model with the lowest level of realism was the model consisting of 62,142 mesh surfaces obtained with the drone camera.

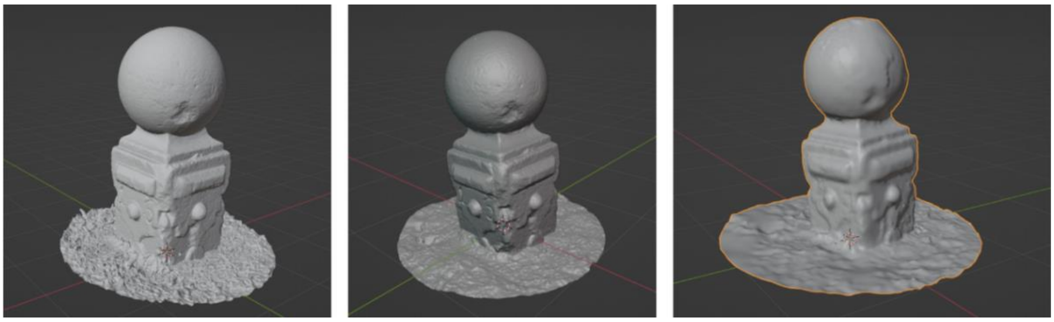


Figure 3.2 Scanned Model of Object 1

Object_2 is also a structure located on the campus of the Politechnika University of Gdansk. The dimensions of this structure are approximately 60x60x100cm in length, and it was created with a shooting route of approximately 600 cm in diameter and two different height levels.

Figure 3.3 Pictures of Object 2

The models obtained by DSLR camera, phone camera and drone shots, respectively, are as follows. Among the models created, the highest level of detail was obtained using a DSLR camera with a mesh face number of 1,249,313. Although the model obtained with the phone camera is lower in terms of realism level, it gave results close to the detail level of the model created with a DSLR with a 600,598 mesh face number. The model with the lowest level of realism was the model obtained using a drone camera with 28,662 surface numbers.

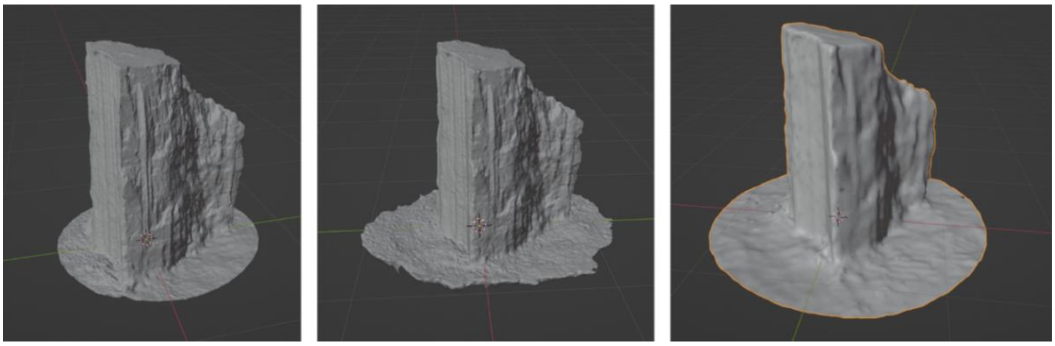


Figure 3.4 Scanned Model of Object 2

Object_3 is urban furniture located on the campus of Politechnika University of Gdansk. The dimensions of this urban furniture are approximately 20x20x170 cm in length and approximately 20x20x90 cm in length. They were created with a shooting route of approximately 600 cm in diameter and two different height levels.

Figure 3.5 Pictures of Object 3

The models obtained by DSLR camera, phone camera and drone shots, respectively, are as follows. Although the highest level of detail among the created models was obtained using a DSLR camera with a mesh face number of 247.106, the model was deformed during the processing of the scan data. Although the model obtained with the drone camera is low in terms of realism with a 27.127 mesh face number, it has been seen that the deformation rate is lower than the DSLR. The model produced from the phone camera shots, on the other hand, is seen as the model at the lowest level in terms of realism and deformation, although it is formed with much more surfaces than other models with a 620,000 mesh surface number.

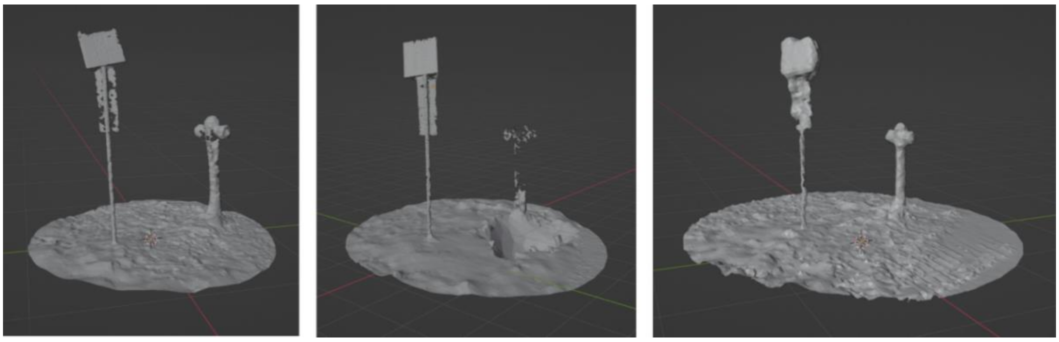


Figure 3.6 Scanned Model of Object 3

Object_4 is a small and singular urban building located on the campus of Politechnika University of Gdansk. The dimensions of this structure are approximately 250x350x750 cm in length, and the approach was created with a 12 m diameter shooting route and 4 different height levels.

Figure 3.7 Pictures of Object 4

The models obtained by DLSR camera, phone camera and drone shots, respectively, are as follows. Among the models created, the highest level of detail was obtained using a DSLR camera with a mesh surface number of 1.522.961. The model with the lowest level of realism and precision is seen as the model obtained using a drone camera with a 258.958 mesh surface number. The images obtained with the phone camera were not sufficient to produce the model, and the mesh model could not be produced.

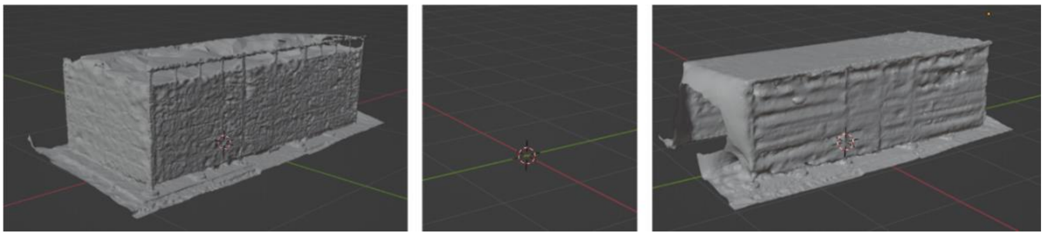


Figure 3.8 Scanned Model of Object 4

Model_5 is an urban building located on the campus of the University of Gdansk. These structures and their surroundings were shot using a drone camera, and a mesh model was created. The model, which includes 2,210,138 mesh faces, has been examined and interpreted in terms of the detail levels of urban and natural structures.

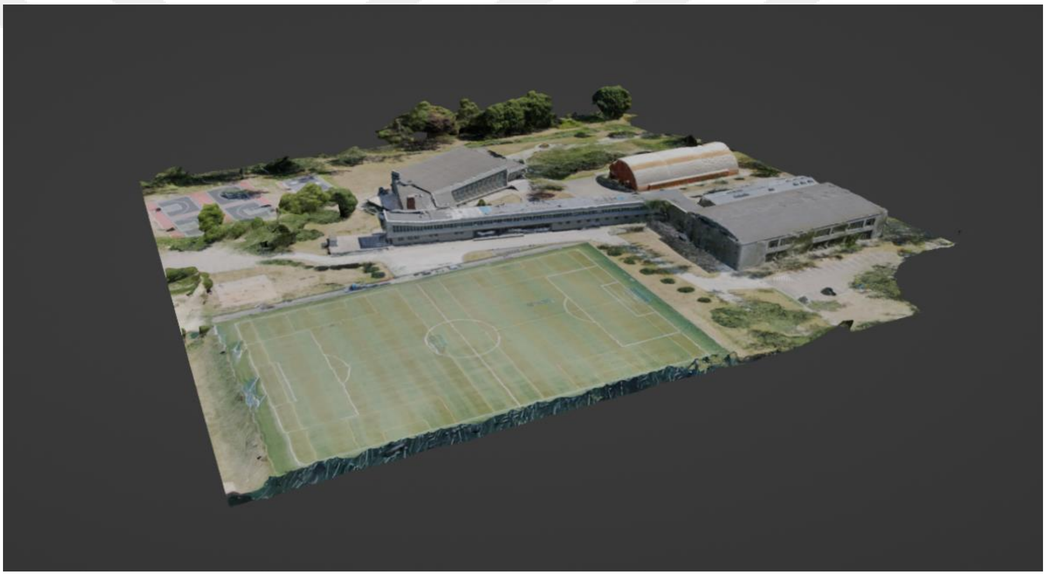


Figure 3.9 Gdansk Politechnika Campus

The blocks in the campus buildings were deformed in the parts that were close to the urban vegetation, as predicted before, and deformation in their dimensional accuracy was observed.

Figure 3.10 Aerial Pictures of Gdansk Politechnika Campus

When the blocks in the open area and its surroundings were examined, it was seen that the structures were scanned successfully and in detail, and the mesh model was produced with high dimensional accuracy.

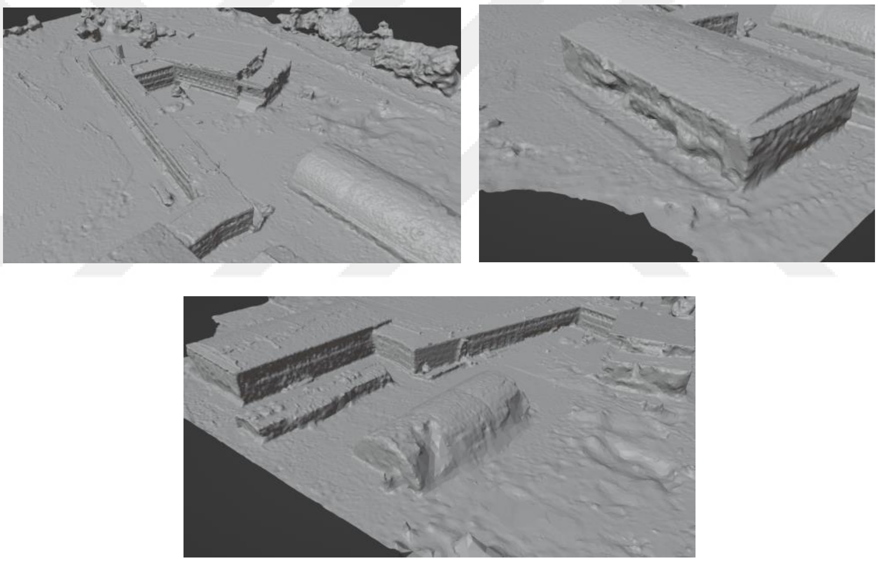


Figure 3.11 Scanned Model of Gdansk Politechnika Campus

3.3.3 Evaluation of Cameras Used by the Obtained Models

When the mesh models obtained using a DSLR camera were examined, it was determined that the dimensional accuracy and level of detail were the highest in direct proportion to the number of mesh surfaces. Although the DSLR camera was used only from the human perspective in the study, it is also possible to use such cameras with drone and aircraft systems.

In terms of dimensional accuracy and level of detail for small-scale urban objects, network models made with a phone camera are comparable to those made with a DSLR camera. However, the level of data obtained and the shooting distances were found to be insufficient for large-scale urban spaces.

Examining the mesh models created by drone cameras reveals that their footage covers a larger area than that of other cameras, allowing for the scanning of larger areas with the same number of shots. However, this is not the best method for creating models with enough detail for small-scale urban objects. However, they are less sensitive to deformation in creating mesh models than DSLR cameras and thus are not as suitable for scanning large-scale urban settings as DSLR cameras. Nevertheless, these types of cameras are appropriate for scanning urban spaces at building size and in open space.

When the models produced with different camera types and urban objects are examined, it is observed that the models produced with DSLR cameras give the most realistic and dimensionally accurate results. The fact that level of detail and dimensional accuracy are the most important criteria for urban representation models shows that the most optimal method for producing these models should be a DSLR camera.

On the other hand, the fact that models with a realistic level close to the models produced with a DSLR camera are able to be produced with a smaller mesh face number compared to the scans made with a phone camera and drone camera shows that the mesh models obtained with the DSLR camera need model-level optimization. In the results part of the study, the relationship between this optimization requirement and the scale of the surveyed urban area will be determined.

3.4 Selecting the Photogrammetric Scanning Scales

Depending on their size, urban area plans are prepared at various scales. For example, master plans are usually developed between 1/500 and 1/25,000, but architectural projects are usually scaled between 1/50 and 1/200. As a result, the analysis and presentation techniques of both disciplines should be included in the proposals created in the field of urban design. For this reason, digital twins to be used in urban design should be exhibited in many dimensions, from urban scale to building scale.

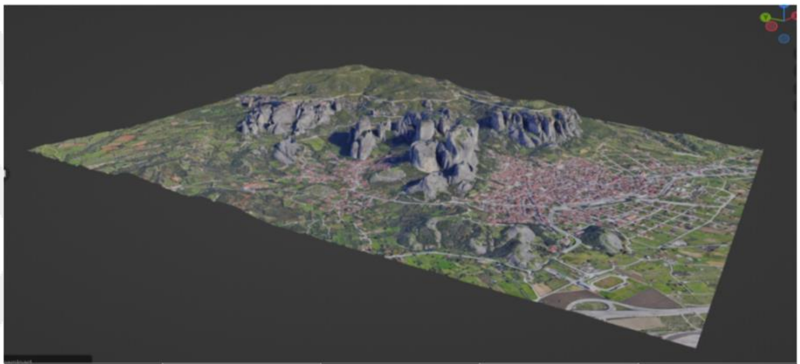
CHAPTER FOUR

MATERIALS

4.1 City Scale

This scaled model contains most of the morphology of a city. Such models include land topology, non-urban green areas, and urban space. It is a scale that is the area of interest of the city and regional planning profession. Long observation distances are often used to scan such a large area created with mostly UAV drones or planes.

4.1.1 Model 1 / Meteora City



Model number	Scale	Model	Area m2	Face amount
Model_1	Regional,landscape	Metaora	14.746.340	50.000

Figure 4.1 Model of Meteora City (*Meteora, Greece - Download Free 3D Model by Fotis Giagkas (@fogiagas)*, 2018)

4.1.2 Model 2 / Hamburg City

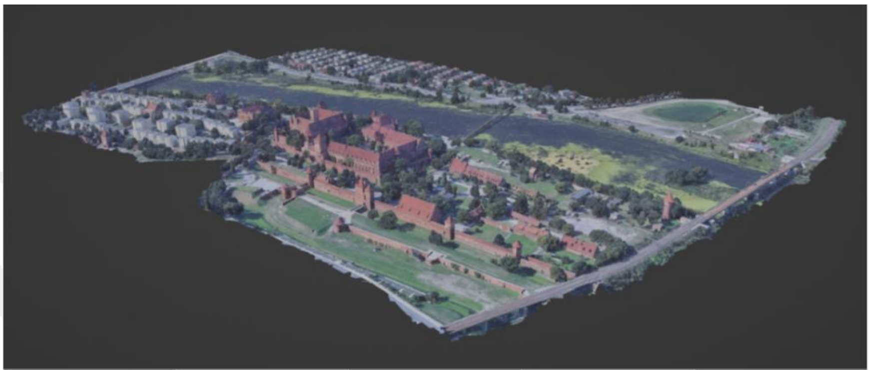
Model number	Scale	Model	Area m2	Face amount
Model_2	Regional,landscape	Hamburg	4.923.444	740.832

Figure 4.2 Model of Hamburg City (*Hamburg City District Large 3D Scan - Download Free 3D Model by Laslo.S*, 2019)

4.2 Neighborhood Scale

The models examined at this scale include models that can focus on the texture of the city and generally include more than one neighborhood unit and urban green areas. These models, which are in the field of interest of the city planning discipline, are generally created using UAV drones.

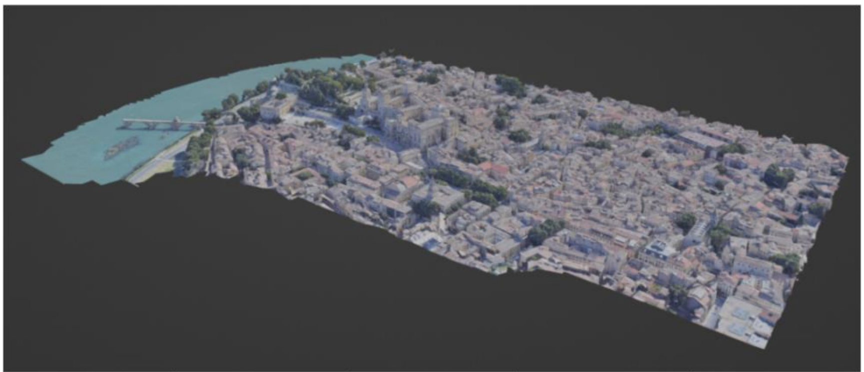
4.2.1 Model 3 / Malbork Castle



Model number	Scale	Model	Area m2	Face amount
Model_3	Neighborhood	Malborg Castle	834.112	1.526.516

Figure 4.3 Model of Malbork Castle (*Castle of the Teutonic Order in Malbork, Poland - Download Free 3D Model by Brian Trepanier (@CMBC)*, 2022)

4.2.2 Model 4 / Palace Of Popes



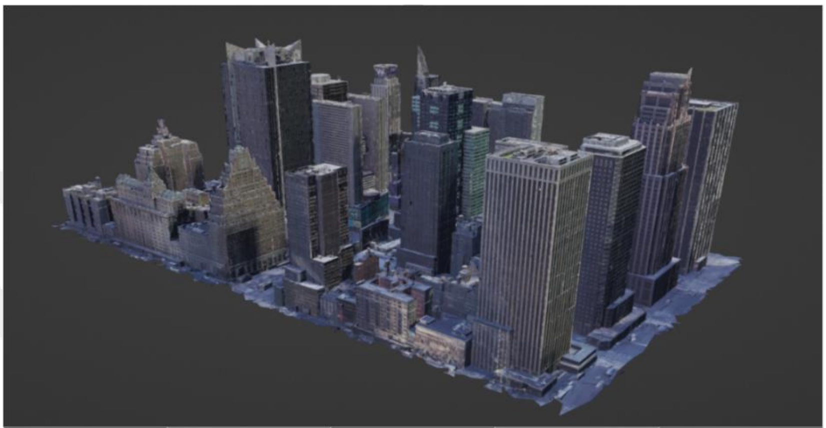
Model number	Scale	Model	Area m2	Face amount
Model_4	Neighborhood	Palace of Popes	600.483	1.066.693

Figure 4.4 Model of Place of Popes (*Palace of the Popes, Avignon, France - Download Free 3D Model by Brian Trepanier (@CMBC)*, 2022)

4.3 Square Scale

The models examined at this scale generally include models that contain public urban spaces and one or more building blocks around them. Models that can be examined within the city planning and urban design professions are generally created with UAV drones.

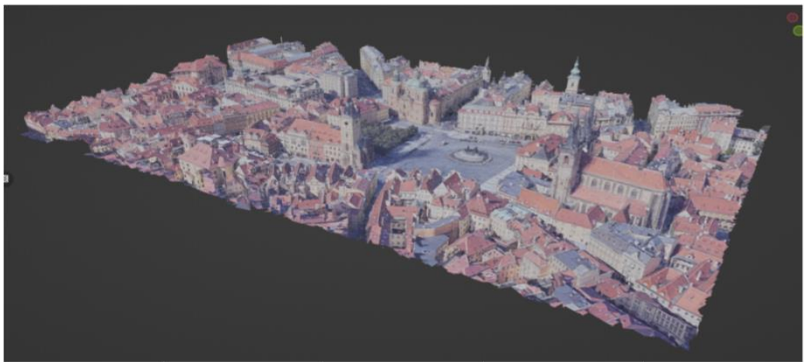
4.3.1 Model 5 / Times Square



Model number	Scale	Model	Area m2	Face amount
Model_5	Square	Times Square	185.325	1.367.756

Figure 4.5 Model of Times Square (*Times Square, New York City, NY, USA - Download Free 3D Model by Brian Trepanier (@CMBC)*, 2021)

4.3.2 Model 6 / Prague Old Town



Model number	Scale	Model	Area m2	Face amount
Model_6	Square	Prague Old Town	128.810	1.540.319

Figure 4.6 Model of Praque Old Town (*Prague Castle, Prague, Czech Republic - Download Free 3D Model by Brian Trepanier (@CMBC)*, 2021)

4.4 Architectural Scale

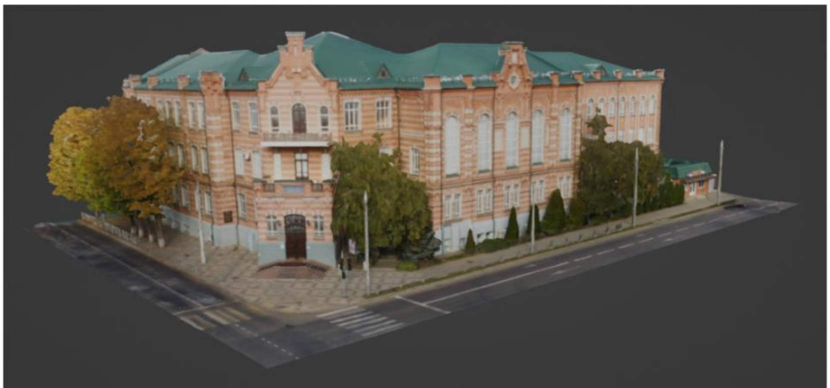
The models examined at this scale include models that contain urban space and landscape at the scale of a singular-plural building or building block. Such models are fields of interest for the architecture and urban design professions and can usually be created with UAV drones and DSLR camera equipment.

4.4.1 *Model 7 / Ship Repair Area*

Model number	Scale	Model	Area m2	Face amount
Model_7	Architectura	Ship Repair Area	6.906	999.703

Figure 4.7 Model of Ship Repair Area (*General Ship Repair - Download Free 3D Model by Katie Wolfe (@katiewolfe)*, 2022)

4.4.2 *Model 8 / City Block*



Model number	Scale	Model	Area m2	Face amount
Model_8	Architectura	Warsaw Block	4.700	449.809

Figure 4.8 City Block (*Институт Физкультуры, Краснодар (КГУФКСТ) - Download Free 3D Model by Mikhail Volkov (@mgv)*, 2021)

4.5 Street Scale

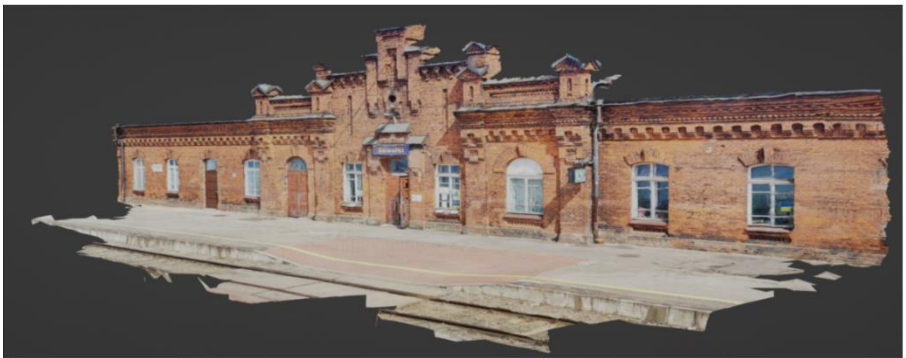
The models examined at this scale include models that contain urban space and landscape at the scale of a singular-plural building or facade. Such models are fields of interest for the architecture and urban design professions and can usually be created with UAV drones and DSLR camera equipment.

4.5.1 Model 9 / Police Station

Model number	Scale	Model	Area m2	Face amount
Model_1	Street And Facede	Police Station	422	1.538.550

Figure 4.9 Model of Police Station (*Southern District Police Station - Download Free 3D Model by Katie Wolfe (@katiewolfe)*, 2022)

4.5.2 Model 10 / Train Station



Model number	Scale	Model	Area m2	Face amount
Model_1	Street And Facede	Train Station	112	1.187.058

Figure 4.10 Model of Train Station (*Suwalki, Railway Station - Download Free 3D Model by Zhenkoest (@zhenko)*, 2022)

4.6 Comparing The Models

In this section, in order to compare the optimization levels of open source models produced with different levels of detail and scales, first the face amount of the models in total and then the face amount of the models per m2 area will be tabled and examined.

The size scales of the models, the area sizes on the basis of m2, and the total surface numbers are as in the table below.

Model Number	Scale	Model	Area m2	Faces
Model_1	City	Meteora	14.746.340	500.000
Model_2	City	Hamburg	4.923.444	740.832
Model_3	Neighborhood	Malborg Castle	834.112	1.526.516
Model_4	Neighborhood	France Place Of Popes	600.483	1.066.693
Model_5	Square	Times Square	185.325	1.367.756
Model_6	Square	Prague Old Town	128.810	1.540.319
Model_7	Architectural	Ship Repair Area	6.906	999.703
Model_8	Architectural	Warsaw City Block	4.700	449.809
Model_9	Street And Facede	Police Station	422	1.538.550
Model_10	Street And Facede	Train Station	112	1.187.058

Table 4.1 Model Descriptions

Table 1 shows that, despite being the largest models in terms of m2 area, city-scale models are also the ones that, on average, have the fewest faces. This is because, in order to be perceived realistically at the urban scale, less model mesh detail is required than at other scales. Urban scale models can be made more efficiently than others since the specifics of green spaces, urban texture, and urban landscape may be created with fewer faces and the use of raster data.

Among the examined models, the other ones, which were created with the least number of surfaces on average, are architectural scale ones. The reason for this is that urban texture has a much more complex and organic texture when compared to a single architectural element. When the flat surfaces of architectural elements are not scanned with enough distance to contain the physical texture of the surface, they can be created with a much smaller mesh surface than the organic ones.

We can observe that the neighborhood unit and urban square scale models in Table 1 have comparable surface numbers when we look at their face numbers. The models made at these scales take a closer look at the distinctive elements of the urban environment. At those sizes, the urban components—landscape, structures, and open spaces—are seen as pieces of the larger metropolitan domain. These models produce models with sufficient realism for the representation of architectural space when viewed at proper observation distances for their scale. It may be concluded that the average degree of mesh detail for a suitable and realistic urban space representation is between 1,000,000 and 1,500,000 faces, taking into account the number of common surfaces contained in both sizes.

In order to better understand the optimization needs of the models selected for the study, models are generalized by the mesh face per area. By the resolution level accepted as 1K size, the represented areas of determined scales are calculated on the basis of m2 area. 1920x1080 pixel dimensions can be accepted as ~68x~38 cm. The areas on a m2 basis, which these lengths indicate as a bird's eye view, are as following table.

Scale	Width	Height	Area m2
1x1	0,68m	0,38m	0,2584
1x50	34m	19m	646
1x500	340m	190m	64600
1X1000	680m	380m	258 400
1X5000	3400m	1900m	6460000
1X100000	68000m	38000m	2584000000

Table 4.2 Screen Proportions and Their Represented Areas

According to the scale based area sizes reached in Table 2, the face numbers per m2 of the examined models were calculated. The table below shows the number of faces by calculated area.

Model Number	Area m2	Faces	646m2	64600m2	258400m2	6460000m2	2584000000m2
Model_1	14.746.340	500.000	22	2.190	8.761	219.037	87.614.961
Model_2	4.923.444	740.832	97	9.720	38.882	972.038	388.815.205
Model_3	834.112	1.526.516	1.182	118.225	472.900	11.822.505	4.729.002.033
Model_4	600.483	1.066.693	1.148	114.755	459.020	11.475.490	4.590.196.079
Model_5	185.325	1.367.756	4.768	476.768	1.907.072	47.676.804	19.070.721.727
Model_6	128.810	1.540.319	7.725	772.491	3.089.965	77.249.132	30.899.652.946
Model_7	6.906	999.703	93.514	9.351.407	37.405.626	935.140.657	374.056.262.960
Model_8	4.700	449.809	61.825	6.182.481	24.729.925	618.248.115	247.299.245.957
Model_9	422	1.538.550	2.355.221	235.522.109	942.088.436	23.552.210.900	9.420.884.360.190
Model_10	112	1.187.058	6.846.781	684.678.096	2.738.712.386	68.467.809.643	27.387.123.857.143

Table 4.3 Model Face Amounts According to Represented Areas

When Table 3 is examined, it is seen that in models 1 and 2, which are urban scaled models, a 1/50 scaled representation of an urban space is formed between 22 and 97 faces. It cannot be expected that the model created with this many faces will reach realistic detail limits. On the other hand, we observe that models 9 and 10 form a representation of an urban space with a scale of 1/100000, between 9.4 and 27.3 trillion faces. Models created with this many faces cannot be displayed on common or even high quality computers used in the field of architecture. Therefore, this situation necessitates establishing a correlation between the level of detail (LOD), observation distance (OD), and number of displayable faces for a digital urban twin model that will realistically contain all scales of architecture and urban planning.

4.7 Optimization Points With Using Observation Distances

Through cameras positioned at specific observation distances, the models were shown in a three-dimensional (3D) digital environment to help researchers better understand the relationship between the level of detail (LOD) and observation distance (OD). The illustration that serves as a good example below specifies the observation distances.

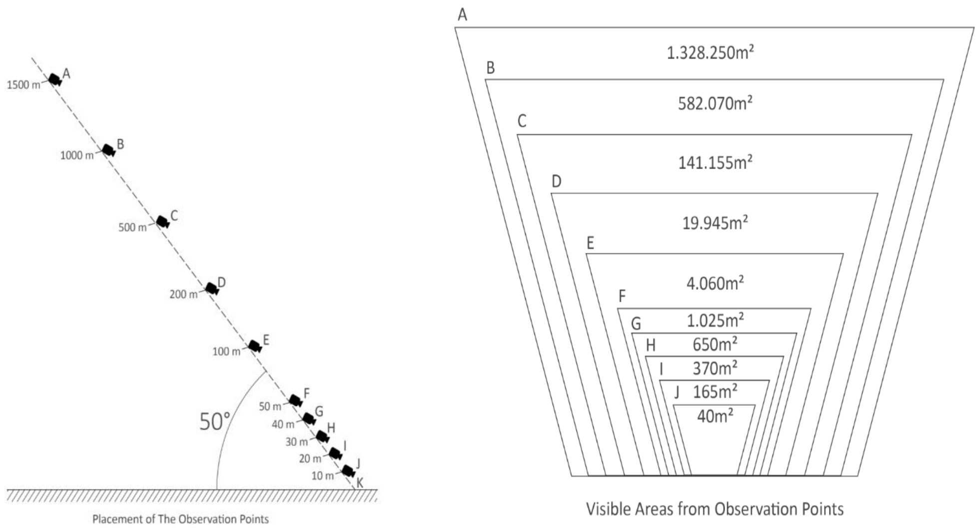


Figure 4.11 Camera Settings and Observed Areas

Identical cameras were positioned at 10, 20, 30, 40, 50, 100, 200, 500, 1000, and 1500 meter intervals and at a 50-degree angle toward the K point. Each camera has a 50mm focal length and no depth of field effect. The chosen cameras were selected while the models were being examined from the farthest one at a distance that could encompass the entire model and from the closest one at a distance where the model was entirely distorted and no further examination was required. The distortion distances of the mesh models are picked out for each model separately.

The calculated zones are displayed in the illustrative graph above for all cameras. Camera A is approximately 1,328,250 m2, Camera B to ~582,070 m2, Camera C to ~141,155 m2, Camera D to ~19,945 m2, Camera E to ~4.060 m2, Camera F to ~1.025 m2, Camera G to ~650 m2, Camera H to ~370 m2, and Camera J to ~40 m2 of area.

4.7.1 Distortion Point of City Scaled Models

Images were taken with A, B, C, D, E, and F cameras located between 1500 meters and 50 meters in urban scale models.

4.7.1.1 Model 1 Meteora City

Figure 4.12 Distortion Point of Model_1

At point A, the mesh model did not show any distortion; nevertheless, at point B, the model's texture showed distortions, and at point D, the surface's corners started to reveal themselves. Point B can be used as the distortion distance at the level of detail (LOD).

4.7.1.2 Model 2 Hamburg City

Figure 4.13 Distortion Point of Model_2

At locations A and B, the mesh model did not display any distortion; nevertheless, starting at point C, the model texture shows distortions, and starting at point E, the corners of the surface begin to appear. The setting for the distortion distance at the level of detail (LOD) is point C.

4.7.2 Distortion Point of Neighborhood Scaled Models

Images were taken with B, C, D, E, and F cameras located between 1000 meters and 50 meters in neighborhood-scaled models.

4.7.2.1 Model 3 Malbork Castle

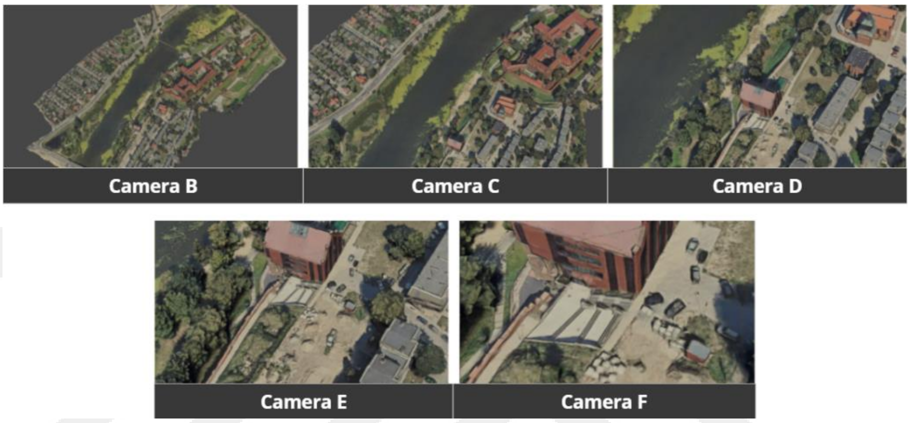


Figure 4.14 Distortion Point of Model_3

At points B and C, there was no distortion visible on the mesh model, but starting at point D, distortions can be seen in the texture of the model, and starting at point E, the corners of the surface can be seen. The setting for the distortion distance at the level of detail (LOD) is point C.

4.7.2.2 Model 4 Place of Popes

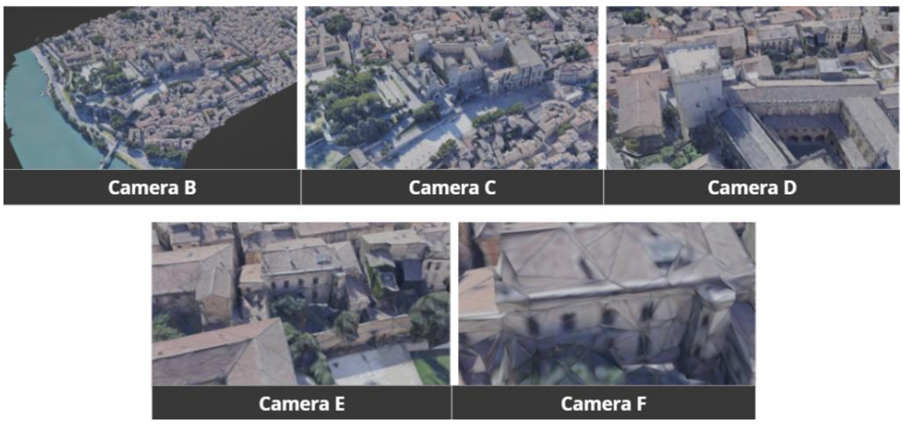


Figure 4.15 Distortion Point of Model_4

At points B and C, there was no distortion visible on the mesh model, but starting at point D, distortions can be seen in the texture of the model, and starting at point E, the corners of the surface can be seen. The setting for the distortion distance at the level of detail (LOD) is point C.

4.7.3 Distortion Point of Public Square Scaled Models

Images were taken with C, D, E, and F cameras located between 500 meters and 50 meters in public square-scaled models.

4.7.3.1 Model 5 Times Square

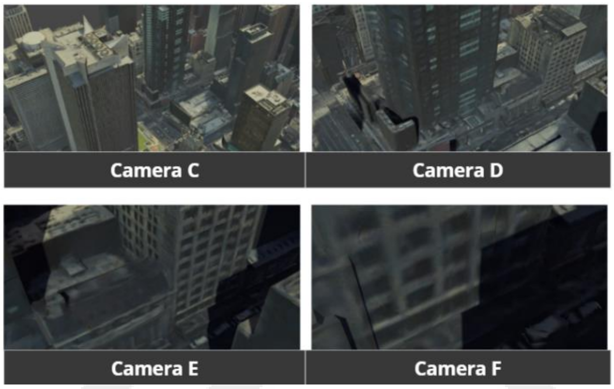


Figure 4.16 Distortion Point of Model_5

At points C and D of the model, there was no distortion visible on the mesh; nevertheless, starting at point E, distortions are visible in the texture of the model, and starting at point F, the corners of the surface are visible. You can set point E to represent the distortion distance at the level of detail (LOD).

4.7.3.2 Model 6 Prague Old Town

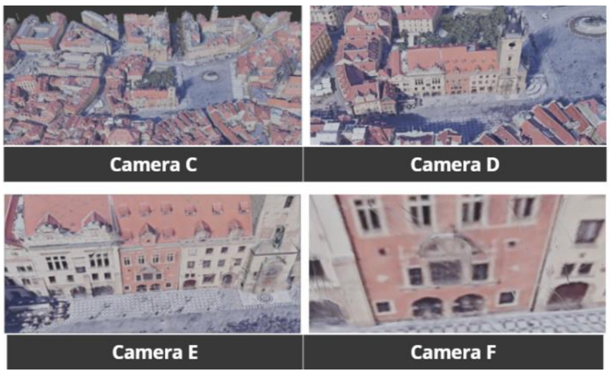


Figure 4.17 Distortion Point of Model_6

At points C, D, and E on the model, there was no distortion evident, but starting at point F, the distortions could be seen in the model's texture. Point F can be used to set the distortion distance at the level of detail (LOD).

4.7.4 Distortion Point of Architectural Scaled Models

Images were taken with D, E, F, G, H, I, and J cameras located between 100 meters and 10 meters in architectural scale models.

4.7.4.1 Model 7 Ship Repair Area

Figure 4.18 Distortion Point of Model_7

Points D, E, F, and G on the model's mesh did not demonstrate any distortion, but starting at point H, the model's texture shows distortions, and starting at point I, the corners of the surface start to show. The setting for point H is the distortion distance at the level of detail (LOD).

4.7.4.2 Model 8 Building Block

Figure 4.19 Distortion Point of Model_8

At points D, E, F, and G on the mesh model, there was no distortion visible; nevertheless, starting at point H, the texture of the model reveals distortions, and starting at point I, the corners of the surface are visible. It is possible to set point H to represent the distortion distance at the level of detail (LOD).

4.7.5 Distortion Point of Street and Facade Scaled Models

Images were taken with E, F, G, H, I, and J cameras located between 50 meters and 10 meters in street and facade scaled models.

4.7.5.1 Model 9 Police Station

Figure 4.20 Distortion Point of Model_9

Points E, F, and G on the mesh model did not show any distortion; however, starting from point I, the corners of the surface can be seen, and the distortions can be seen in the texture of the model. Point I can be specified as the distortion distance at the level of detail (LOD).

4.7.5.2 *Model 10 Train Station*

Figure 4.21 Distortion Point of Model_10

Points E, F, and G on the mesh model did not display any distortion, however starting from point I, the distortions can be seen in the model's texture and can be seen as the surface's corners. It is possible to assign point I to the distortion distance at the level of detail (LOD).

CHAPTER FIVE

RESULTS OF THE STUDY

5.1 Results

5.1.1 Observation Ranges of the Models

The table below shows the ratio of the total number of surfaces that each model contains to the number of surface areas that make up the fields displayed on the screen at observation points. For this, it should be assumed that the entire scene displayed is covered with similar quantitative models. The yellow boxes are marked with previously identified distortion points.

Model Number	Total Face	1500 m	1000 m	500 m	200 m	100 m	50 m	40 m	30 m	20 m	10 m
Model_1	100	8,0	4,2	1,1	0,2	0,0	0,0	0,0	0,0	0,0	0,0
Model_2	100	33,0	16,0	3,8	0,5	0,1	0,0	0,0	0,0	0,0	0,0
Model_3	100	201,0	88,1	40,7	8,1	1,7	0,4	0,0	0,0	0,0	0,0
Model_4	100	211,9	92,8	36,3	3,1	0,7	0,1	0,0	0,0	0,0	0,0
Model_5	100	518,2	227,1	55,1	4,2	0,4	0,1	0,0	0,0	0,0	0,0
Model_6	100	955,5	418,7	101,5	14,3	3,5	0,6	0,0	0,0	0,0	0,0
Model_7	100	19939,7	8738,0	2119,0	299,4	60,9	7,1	3,3	1,5	0,5	0,1
Model_8	100	31997,8	14022,2	3400,5	480,5	97,8	24,7	18,1	10,7	4,5	0,4
Model_9	100	32715,5	14336,7	3476,7	491,3	100,0	55,6	44,9	24,0	7,9	6,3
Model_10	100	323087,8	141584,6	34335,0	4851,5	987,6	249,3	158,1	90,1	65,8	24,4

Table 5.1 Distortion Points and Observation Distances

The surface number ratios at the distortion points can be interpreted as the sensitivity of the models. Models with less proportion of surface at the point of distortion have a wider display, i.e. the scope of use. Likewise, models with a higher proportion surface rate at the distortion point will have a narrower display, i.e. a smaller area of use.

It has been concluded that the sensitivities of models 1 and 2, which are city-scale models, are close to each other, this is due to the fact that the spatial elements located in large urban areas are mostly shared, and the structures with different spatial characteristics in non-urban areas do not have a great impact on the sensitivity of the model.

When the neighborhood-scale models are examined, it is seen that the two models with different characteristics are quite different from each other in terms of surface ratios at the observation distance of 1500 meters and at their distortion point distances. The reason for this is thought to be that the effects of different city characteristics on the sensitivity increase as the scale gets smaller in model 3, where the natural environment is intense, and model 4 which includes mostly the built environment. This is because it is seen as an effect of the physical structure on the data collection requirements and therefore on the data density used while creating the spaces.

In square-scale models there are models that belong to two different city characteristics, similar to neighborhood-scale models. Model 5 represents a high-density urban space, and model 6 represents a more organic and low-density urban space. It is seen that the number of surfaces included by the models at the same observation distances is quite different from each other and this difference gets wider as the observation distance increases. On the other hand, it was observed that both models displayed similar surface numbers when they reached the distortion point. This situation can be interpreted as the effect of urban morphology on model sensitivity is greater than the level of architectural detail at this scale.

Although the distortion points of the models in the architectural and street scales are at similar distances within the same group, it is seen that they are quite different from each other in terms of model sensitivities. The models are included; an industrial area in model 7, a building block in model 8, a single building in model 9 and a building facade in model 10. The reason for this difference is thought to be related to the level of physical detail that increases as the distance decreases.

5.1.2 Evaluation of Model Statistics According to Distortion Points and Optimization Limits

Model Number	Total Face	1500 m	1000 m	500 m	200 m	100 m	50 m	40 m	30 m	20 m	10 m
Model_1	500.000	39787	**21089**	5731	945	210	42	0,0	0,0	0,0	0,0
Model_2	740.832	244163	118834	**28351**	3881	1053	331	0,0	0,0	0,0	0,0
Model_3	1.526.516	3067983	1344461	620871	**124369**	25286	5895	0,0	0,0	0,0	0,0
Model_4	1.066.693	2259949	990362	387545	**32581**	7976	1385	0,0	0,0	0,0	0,0
Model_5	1.367.756	7087982	3106118	753251	57436	**5940**	1423	0,0	0,0	0,0	0,0
Model_6	1.540.319	14494178	6351684	1540319	220992	53457	**9981**	0,0	0,0	0,0	0,0
Model_7	999.703	66578964	29176442	7075451	999701	609307	70647	32619	14638	**4643**	748
Model_8	449.809	147193374	64503541	15642471	2210148	449809	111069	81565	48195	**20304**	1858
Model_9	1.538.550	503467839	220631254	53504318	7559705	1538550	855827	690180	368756	122031	**96797**
Model_10	1.187.058	3851861607	1687974861	409343379	57836735	11770924	2969556	1882072	1070084	781136	**290094**
			DP1	DP2		DP3			DP4	DP5	

Table 5.2 Optimization Zones According to Observation Distances and Distortion Points

The distortion points to be used when determining LOD levels and surface density, which is an important element for system optimization, are combined in the table above. The regions shown by the cut lines represent the distortion points specified for each scale, while the coloured boxes represent the surface amounts.

When the boxes shown in red are specified, it is assumed that the models from specified distances will fill the entire computer screen with models with the same surface density. According to this, between 1-10,000,000 surfaces were rated between red and blue. When evaluating the LOD, surface numbers shown in red should not be preferred, it should be chosen over the previous observation distance from itself. When determining the maximum observation distances of the LOD groups, the model with the highest surface density in its scale should be used, assuming that it will go out of the optimization limits sooner.

When determining the minimum distances of the LOD groups, the visual distortion points shown by the cut line should be assessed. Since the systems, inputs and applications used in the production of the evaluated models are not known, the distance of the earliest distorted model in their own scale should be chosen by taking into account the margins of error and production differences.

5.1.3 Defining the LOD Optimization Levels

Model Number	Total Face	1500 m	1000 m	500 m	200 m	100 m	50 m	40 m	30 m	20 m	10 m
Model_1	500.000	39787	**21089**	5731	945	210	42	0,0	0,0	0,0	0,0
Model_2	740.832	244163	118834	**28351**	3881	1053	331	0,0	0,0	0,0	0,0
Model_3	1.526.516	3067983	1344461	620871	**124369**	25286	5895	0,0	0,0	0,0	0,0
Model_4	1.066.693	2259949	990362	387545	**32581**	7976	1385	0,0	0,0	0,0	0,0
Model_5	1.367.756	7087982	3106118	753251	57436	**5940**	1423	0,0	0,0	0,0	0,0
Model_6	1.540.319	14494178	6351684	1540319	220992	53457	**9981**	0,0	0,0	0,0	0,0
Model_7	999.703	66578964	29176442	7075451	999701	609307	70647	32619	14638	**4643**	748
Model_8	449.809	147193374	64503541	15642471	2210148	449809	111069	81565	48195	**20304**	1858
Model_9	1.538.550	503467839	220631254	53504318	7559705	1538550	855827	690180	368756	122031	**96797**
Model_10	1.187.058	3851861607	1687974861	409343379	57836735	11770924	2969556	1882072	1070084	781136	**290094**

Table 5.3 Optimized Zones by Urban Scales

When urban-scale models shown in red are viewed from a 500-meter viewing distance, one model is already distorted and the other is on the distortion point, but both models do not reach the problematic surface density for system optimization when observed even above 1500 meters. Therefore, it has been concluded that the city scale, which is the largest, can be considered together with the neighborhood scale. On the other hand, it represents the final qualified models that can be observed from a distance of 200 meters for neighborhood-scale models shown in yellow. Neighborhood scale models when observed from 1500 meters, we see that the surface amount that will cause the optimization problem is approaching, but that it does not pass. However, this limit has been crossed on the square scale, which is a smaller scale.Considering that these models on the scale of the city and the neighborhood meet conceptually with the scope of the Master plans; It has been concluded that between the observation distances between 1500 and 500 meters, the models at the Urban and Neighborhood scales can be evaluated as the LOD_1000 level, which is the most comprehensive optimization region.

The observation range of the square scale models represented in green in the table was found to be between 50 meters, the next distance from the lowest deterioration point, and 500 meters, the previous observation distance before reaching the number of dense surfaces marked with red. Even when the models reach their distortion points, they have a distinctively higher surface ratio compared to the models in the previous and subsequent scales; also, considering that they represent the urban design scale by itself, it was found necessary for the models at this scale to form their own optimization region, as LOD_2000 level, to decompose the level of detail from the others. Since the urban morphology at this scale is thought to have a great impact on the model characteristic, it can be suggested that the LOD_2000 level be considered together with a subcategory, LOD_2050, in order to distinguish different city characters and detail levels.

Architectural scale models expressed in turquoise color and street-scale models displayed in blue color have been shown to share their observation distances in areas prior to 50 meters, which are the minimum observation level of the previous LOD level. Since LOD categorization aims at the highest possible optimization at each level, these two scales should be evaluated together. For this reason, it was found appropriate to evaluate the architectural scale with the model characteristic of the street scale, which is the next scale. When the distortion points of the street scale models are examined, it is seen that they share the observation distance of 10 meters, therefore the region between 50 meters and 20 meters constitutes the optimization region of the architectural and street scale models, as LOD_3000 level. However, the qualified observation distances of architectural scale models can increase up to 200 meters, but the fact that street scale models exceed the optimization limits at this distance may require them to be examined as two groups in a study that will focus specifically on this scale. For this, it may be necessary to examine LOD_3000, which is the level representing architectural and street scale models, with a subcategorization as the LOD_3050 level for wider representations.

Considering that a level covering a distance of 10 meters cannot be produced in the categorization, and the models produced at this scale in the urban area are generally produced for preserved areas and special areas for high visual consistency. For consistency, the LOD_4000 level should be added to the categorization for private and protected areas of 10 meters and below.

After examining the table in terms of observation distances and deterioration points, it was determined that LOD_1000 level represented city and neighborhood scales and displayed between 1500 and 500 meters, LOD_2000 levels represented public space and square scale and displayed between 500 and 100 meters, LOD_3000 levels represented architectural and street scales. and 100-20 meters range and finally LOD_4000 level represents private and protected areas and displayed between 20 and 0 meters in line with the selected models and the applications used.

To ensure consistency of categorization and transitivity between models, it is necessary to determine the maximum and minimum number of surfaces that the LOD levels will contain when displayed in the scene. When the deterioration points and surface density data analyzed in the table below are analyzed at each level, the maximum number of surfaces that can be included in the scene has been determined as 3,000,000 surfaces, in accordance with the requirements of LOD_1000 and LOD_3050 levels, and has been determined as the maximum value of each scale. While determining the minimum level, it was determined as 400,000 surfaces by considering the surface density of Model_4 at 500 meters, which is the model containing the highest number of model surfaces among the models containing the lowest number of surfaces that can be used at each level.

After all the evaluations and observations, the LOD system optimization categorization based on the city models created using Scanning methods is as follows.

	Definition	Face Amount (min-max)
LOD_1000	Contains city and neighborhood scale models to be used between 1500-500 meters observation distances	400.000-3.000.000
LOD_2000	Contains square scale models to be used between 500-100 meters observation distances	400.000-1.500.000
LOD_2050	Contains square scale models to be used between 500_100 meters observation distances and may contain more surface numbers than its upper category LOD_2000	1.500.000-3.000.000
LOD_3000	Contains architectural and street scale models for use at observation distances of 100-50 meters	400.000-1.500.000
LOD_3050	Can be used as a subcategory of LOD_3000 level to be used between 50-20 meters observation distances and contains architectural-street scale models	1.500.000-3.000.000
LOD_4000	Contains preserved sites and special area models for use at observation distances below 20 meters	According to max system requiriments

Table5.4 Face Amounts and Definitions of Proposed LOD Categorization for Urbanism

CHAPTER SIX

DISCUSSION AND CONCLUSION

6.1 Discussion

The concept of the digital twin is a very comprehensive concept that is beginning to be accepted by the masses and industries. Although there is a consensus that it will be a useful tool in the urban area, especially in the field of urban design, and even change the habits in this area, there is no consensus on its requirements and sustainability due to the scarcity of application examples. The fact that the development teams are working on different areas of the concept. Considering the speed of technological development, studies on this subject are still very few, some of these limited studies have already lost their validity.

Optimization, which is perhaps one of the most important new discussions brought by the concept of digital twin, has been the subject of this study. It has been discussed whether a realistic representation of the digital twin concept can be used with models created entirely using sensors in the field of urbanization and how a basic optimization method such as LOD can be considered to achieve this goal.

As a result of the study, it has been clearly understood that the existence of a 3D city model with geometric details that can address all scales of the urban planning area with the opportunities provided by today's technology is close to impossible. Even if there is, it is not possible for this model to work in a real-time ecosystem, integrating with the software infrastructure that will reflect the urban digital twin concept. At this point, it is clearly seen that a 3D environment with a holistic level of detail cannot be created in this context without the optimization method and parameters.

The LOD optimization method is a very old and primitive method and can be seen as outdated. However, LOD and its implications form the basis of many new software products for optimization in the 3D space. Optimization is always based on doing the necessary work for the targeted output and not wasting unnecessary resources to achieve the invisible. In addition, the main model categorization existing in applications such as BIM and cityGML, which are widely used in the fields of architecture and urbanism, is based on the LOD concept. For this reason, LOD has been seen as a concept suitable for use in an application such as a digital twin and has therefore been preferred.

From a different point of view, it is noteworthy that the broad framework and limits of the digital twin concept are above its general applicability. However, it may be possible for the infrastructure used to produce these 3D realistic environments to become instantly reproducible within the framework of possible future technological developments in the field of graphics. It is unlikely that graphics processors or AI applications will significantly speed up model production processes such as photogrammetry. In addition, NVIDIA's NeRF technology, which takes its place in the field of 3D graphics, strengthens this idea in a way. In this way, we can focus only on categorization and optimization instead of 3D data, which is processing-intensive to produce, needs to be reproduced and adapted to be updated and optimized before and after production, and still has large file sizes. constitutes the data set. The effects of next-generation graphics processors on digital city representation applications may be a subject of research in the future.

However, it should be added that the material of the study is not a holistic study conducted in a single urban area, the equipment selected to be exactly the same was not used, so it is not known whether these models are the most optimal result product that can be produced. The results of the case study are not consistent enough to establish a standardization in this area due to the use of datasets obtained with open source models covering different urban areas, and also the relative nature of the accepted parameters. It also makes no sense to make such a standardization using only surface numbers. The main purpose of the study is based on how the general lines of a LOD categorization to be made in an urban area can be handled. In this context, it has been observed that a 4-stage categorization can be made for system optimization of the 3-dimensional representation, and this categorization has shown internal consistency in many respects.

6.2 Conclusion

In addition to the 2D CAD and GIS systems that AEC sectors and city planners frequently use today, the urban design field also needs 3D digital representations of the physical urban environment, and for this reason, the interest in the digital urban area is increasing. Although three-dimensional models and digital city applications created with them and the production of 3D models with remote sensing systems are not new, they had a limited area of use in the sector since the cost and time of creating digital data were quite high. This is the case of graphics processing technologies that have developed over the past decade; technologies such as photogrammetry and lidar become much more accessible with new applications and hardware; and the digital gaming industry has grown in size and the tools used in this field have opened up significant new possibilities. The interest and applications of digital city labs and local governments to the digital twin concept, whose applications in the urban area are still becoming popular, are increasing.

This raises the question of what opportunities and problems will be caused by the use of game engines such as the unreal engine, where some of the current applications in the field of digital twin are carried out. One of the main problems in the use of 3D models with dense surfaces created by detection methods such as photogrammetry and lidar in game engines is the optimization problem. models with such a high number of surfaces require high-spec hardware from the graphics processors available in computers that are heavily used in the AEC market. In addition, problems such as the use of tools aimed at participatory planning, which is one of the current trends of 3D city systems, and the ability to offer platforms such as city information systems as web services, necessitated the reconsideration of LOD optimization through city forms.

Creating a holistic 3D city model containing realistic 3D data to be used in urban design stages should be considered as an optimization problem, as in any industry working with complex, large and diverse data sets. According to this study, holistic city-sized 3D representation with street texture-level detail brings in enormous amounts of 3D data and renders it unusable and uninteresting with existing hardware and software technology that designers often work with. Likewise, the reverse cannot be used to make inferences about urban space at lower observation distances. However, according to the produced calculations and graphic tables, there is a relationship between the visual quality of digital representations, the amount of 3D model faces, urban texture and observation distances, and this relationship can be used to determine LOD levels. By increasing the model quality at each optimization point, the 3D city representation in the game engine can be optimized.

Drawing a clear picture of the LOD categorization setup due to the developing technology and different 3D model characteristics of different urban spaces would be contrary to the nature and consistency of this concept. However, making the decision method applied in the study on an application basis may be important in terms of ensuring the targeted system optimization. In addition, for a LOD categorization in the field of Urbanism, the equivalents of these levels in urban planning, urban design and architecture should be examined separately and the correlation between LOD levels and city scales should be examined.

REFERANCES

Aliabadi, M., & Mirsharafi, S. (2013). *Evolution of BIM and Integrated Sustainable Design Process (From Hand-drafting to ID technology)*.

Anthony Jnr, B. (2021). Managing digital transformation of smart cities through enterprise architecture – a review and research agenda. *Enterprise Information Systems*, *15*(3), 299–331. https://doi.org/10.1080/17517575.2020.1812006

Atzori, L., Iera, A., & Morabito, G. (2010). The Internet of Things: A survey. *Computer Networks*, *54*(15), 2787–2805. https://doi.org/10.1016/j.comnet.2010.05.010

Aydinoglu, A., & Bovkir, R. (2020). DEVELOPING A MOBILE APPLICATION FOR SMART REAL ESTATE INFORMATION. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLIV-4/W3-2020*, 89–94. https://doi.org/10.5194/isprs-archives-XLIV-4-W3-2020-89-2020

Baig, S. (2013). Generalization of buildings within the framework of CityGML. *Geo-Spatial Information Science*, *16*, 247–255. https://doi.org/10.1080/10095020.2013.866617

Batty, M. (2018). Digital twins. *Environment and Planning B: Urban Analytics and City Science*, *45*(5), 817–820. https://doi.org/10.1177/2399808318796416

Beck, M., Ag, V., & Zurich. (2023). *Real-time visualization of big 3D city models*.

Bertoline, G., Wiebe, E., Hartman, N., & Ross, W. (2008). *Technical Graphics Communication* (4th edition). McGraw-Hill Education.

Biljecki, F., Heuvelink, G. B. M., Ledoux, H., & Stoter, J. (2015). Propagation of positional error in 3D GIS: Estimation of the solar irradiation of building roofs. *International Journal of Geographical Information Science*, *29*(12), 2269–2294. https://doi.org/10.1080/13658816.2015.1073292

Biljecki, F., Ledoux, H., & Stoter, J. (2017). Does a Finer Level of Detail of a 3D City Model Bring an Improvement for Estimating Shadows? In A. Abdul-Rahman (Ed.), *Advances in 3D Geoinformation* (pp. 31–47). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-25691-7_2

Biljecki, F., Ledoux, H., Stoter, J., & Zhao, J. (2014). Formalisation of the level of detail in 3D city modelling. *Computers, Environment and Urban Systems*, *48*, 1–15. https://doi.org/10.1016/j.compenvurbsys.2014.05.004

Biljecki, F., Stoter, J., Ledoux, H., Zlatanova, S., & Çöltekin, A. (2015). Applications of 3D City Models: State of the Art Review. *ISPRS International Journal of Geo-Information*, *4*(4), 2842–2889. https://doi.org/10.3390/ijgi4042842

Biljecki, F., Zhao, J., Stoter, J., & Ledoux, H. (2013). Revisiting the concept of level of detail in 3D city modelling. In *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*. https://doi.org/10.5194/isprsannals-II-2-W1-63-2013

Billen, R., Cutting-Decelle, A.-F., Marina, O., De Almeida, J.-P., M., C., Falquet, G., … Zlatanova, S. (2014). 3D City Models and urban information: Current issues and perspectives: European COST Action TU0801. In R. Billen, A.-F. Cutting-Decelle, O. Marina, J.-P. De Almeida, C. M., G. Falquet, … S. Zlatanova (Eds.), *3D City Models and urban information: Current issues and perspectives – European COST Action TU0801* (p. I–118). Liège, Belgium: EDP Sciences. https://doi.org/10.1051/TU0801/201400001

Billen, Roland. (n.d.). *Some issues on 3D Urban GIS*.

Boffi, M., & Rainisio, N. (2017). To Be There, Or Not To Be. Designing Subjective Urban Experiences. In *Urban Design and Representation: A Multidisciplinary and Multisensory Approach* (pp. 37–53). https://doi.org/10.1007/978-3-319-51804-6_4

Bokolo, A., Petersen, S. A., & Helfert, M. (2022). Improving Digitization of Urban Mobility Services with Enterprise Architecture. In P. Mikalef & E. Parmiggiani

(Eds.), *Digital Transformation in Norwegian Enterprises* (pp. 135–150). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-031-05276-7_8

Castle of the Teutonic Order in Malbork, Poland—Download Free 3D model by Brian Trepanier (@CMBC). (2022). Retrieved from https://sketchfab.com/models/51092b2a02484bd1b53547e4aa39021d/embed?autostart=1

Clark, J. H. (1976). *Hierarchical geometric models for visible surface algorithms*. *19*(10).

Coltekin, A., & Reichenbacher, T. (2011). High Quality Geographic Services and Bandwidth Limitations. *Future Internet*, *3*(4), 379–396. https://doi.org/10.3390/fi3040379

Cubukcu, E. (2011). Does the level of visual detail in virtual environments affect the user's spatial knowledge? *Environment and Planning B: Planning and Design*, *38*, 741–752. https://doi.org/10.1068/b37079

Delaney, B. (2000). Visualization in urban planning: They didn't build LA in a day. *IEEE Computer Graphics and Applications*, *20*(3), 10–16. https://doi.org/10.1109/38.844365

Dembski, F., Wössner, U., Letzgus, M., Ruddat, M., & Yamu, C. (2020). Urban Digital Twins for Smart Cities and Citizens: The Case Study of Herrenberg, Germany. *Sustainability*, *12*(6), 2307. https://doi.org/10.3390/su12062307

Digital Twin. (n.d.-a). Unreal Engine. Retrieved from https://www.unrealengine.com/en-US/digital-twins

Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems. (n.d.-b). Retrieved January 15, 2023, from Springerprofessional.de website:https://www.springerprofessional.de/en/digital-twin-mitigating-unpredictable-undesirable-emergent-behav/10588328

Digital twins—Michael Batty, 2018. (n.d.). Retrieved June 4, 2023, from https://journals.sagepub.com/doi/full/10.1177/2399808318796416

Döllner, J., Baumann, K., & Buchholz, H. (2007). *Virtual 3D City Models as Foundation of Complex Urban Information Spaces*. Retrieved from https://www.semanticscholar.org/paper/Virtual-3D-City-Models-as-Foundation-of-Complex-D%C3%B6llner-Baumann/e9aff2a83086dcbc9abea029e95f21e15bcd4788

Dunn, N. (2012). *Digital Fabrication in Architecture*. London: Laurence King Publishing.

El Saddik, A. (2018). Digital Twins: The Convergence of Multimedia Technologies. *IEEE MultiMedia*, *25*(2), 87–92. https://doi.org/10.1109/MMUL.2018.023121167

European Climate, I. and E. E. A. (European C., Alpagut, B., Zhang, X., Gabaldon, A., & Hernandez, P. (2022). *Digitalization in urban energy systems: Outlook 2025, 2030 and 2040*. LU: Publications Office of the European Union. Retrieved from https://data.europa.eu/doi/10.2926/070630

Fan, H., & Meng, L. (2012). A three-step approach of simplifying 3D buildings modeled by CityGML. *International Journal of Geographical Information Science - GIS*, *26*, 1–18. https://doi.org/10.1080/13658816.2011.625947

Fernández-Arango, D., Varela-García, F.-A., González-Aguilera, D., & Lagüela-López, S. (2022). Automatic Generation of Urban Road 3D Models for Pedestrian Studies from LiDAR Data. *Remote Sensing*, *14*(5), 1102. https://doi.org/10.3390/rs14051102

Ford, D. N., & Wolf, C. M. (2020). Smart Cities with Digital Twin Systems for Disaster Management. *Journal of Management in Engineering*, *36*(4), 04020027. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000779

Francisco, A., Truong, H., Khosrowpour, A., Taylor, J. E., & Mohammadi, N. (2018). Occupant perceptions of building information model-based energy visualizations in eco-feedback systems. *Applied Energy*, *221*(C), 220–228.

General Ship Repair—Download Free 3D model by Katie Wolfe (@katiewolfe). (2022). Retrieved from https://sketchfab.com/models/ee2536a947c24610a21ddf7fd66be598/embed?autostart=1

Goodchild, M. F. (2022). Elements of an infrastructure for big urban data. *Urban Informatics*, *1*(1), 3, s44212-022-00001–00005. https://doi.org/10.1007/s44212-022-00001-5

Groger, G., Kolbe, T. H., Czerwinski, A., & Nagel, C. (2008). *OpenGIS® City Geography Markup Language (CityGML) Encoding Standard. Version 1.0.0.* [Report]. Open Geospatial Consortium. https://doi.org/10.25607/OBP-635

Guo, H., Goodchild, M. F., & Annoni, A. (Eds.). (2020). *Manual of Digital Earth*. Springer Nature. https://doi.org/10.1007/978-981-32-9915-3

Hamburg City District Large 3D Scan—Download Free 3D model by Laslo.S. (2019). Retrieved from https://sketchfab.com/models/f47c2f4bcca04af0bb04f2c37fbdc654/embed?autostart=1

Hanzl, M., & Wrona, S. (2004). *Visual Simulation as a Tool for Planning Education—Computer Aided Participation Support*. 500–507. Copenhagen, Denmark. https://doi.org/10.52842/conf.ecaade.2004.500

Härting, R.-C., Reichstein, C., & Sandkuhl, K. (2018). *Determinants to Benefit from Enterprise Architecture Management – A Research Model*. 101–111. Berlin, Germany. Retrieved from https://link.springer.com/chapter/10.1007/978-3-030-04849-5_9

Hofmann, R., Halmshlager, V., Knötter, S., Leitler, B., Pernsteiner, D., Prendl, L., … Traupmann, A. (2022). *Digitalization in Industry – an Austrian Perspective*. Retrieved from https://iea-industry.org/publications/digitalization-in-industry-an-austrian-perspective/

Hristov, P. O., Petrova-Antonova, D., Ilieva, S., & Rizov, R. (2022). ENABLING CITY DIGITAL TWINS THROUGH URBAN LIVING LABS. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information*

Sciences, *XLIII-B1-2022*, 151–156. https://doi.org/10.5194/isprs-archives-XLIII-B1-2022-151-2022

Jelalian, A. V. (1991). *Laser Radar Systems*. Boston: Artech Print on Demand.

Ju, W., Ayalon, S., Goedicke, D., Mandel, I., Lu, B., Lu, J., … Joan, A. (2021). *Digital Twin*.

Karasaka, L., & Makineci, H. (2021). Investigation of 3D Models Acquired with UAV Oblique Images. *Turkish Journal of Geosciences*. https://doi.org/10.48053/turkgeo.980559

Ketzler, B., Naserentin, V., Latino, F., Zangelidis, C., Thuvander, L., & Logg, A. (2020). Digital Twins for Cities: A State of the Art Review. *Built Environment*, *46*(4), 547–573. https://doi.org/10.2148/benv.46.4.547

Lasi, H., Fettke, P., Kemper, H.-G., Feld, T., & Hoffmann, M. (2014). Industrie 4.0. *WIRTSCHAFTSINFORMATIK*, *56*, 261–264. https://doi.org/10.1007/s11576-014-0424-4

Lehner, H., & Dorffner, L. (2020). Digital geoTwin Vienna: Towards a Digital Twin City as Geodata Hub. *PFG – Journal of Photogrammetry, Remote Sensing and Geoinformation Science*, *88*(1), 63–75. https://doi.org/10.1007/s41064-020-00101-4

Lei, B., Janssen, P., Stoter, J., & Biljecki, F. (2023). Challenges of urban digital twins: A systematic review and a Delphi expert survey. *Automation in Construction*, *147*, 104716. https://doi.org/10.1016/j.autcon.2022.104716

Luebke, D., Reddy, M., Cohen, J. D., Varshney, A., Watson, B., & Huebner, R. (2002). *Level of Detail for 3D Graphics* (1st edition). Boston, MA: Morgan Kaufmann.

Luo, W., Hu, T., Zhang, C., & Wei, Y. (2019). Digital twin for CNC machine tool: Modeling and using strategy. *Journal of Ambient Intelligence and Humanized Computing*, *10*(3), 1129–1140. https://doi.org/10.1007/s12652-018-0946-5

McCall, D. W. (2021). *What Is Digital Twin Technology And Why It's Important*. Retrieved from https://www.unrealengine.com/en-US/blog/what-is-a-digital-twin

McCall, D. W. (n.d.). *51World creates digital twin of the entire city of Shanghai*. Retrieved from https://www.unrealengine.com/en-US/spotlights/51world-creates-digital-twin-of-the-entire-city-of-shanghai

Megahed, N., & Hassan, A. (2022). Evolution of BIM to DTs: A Paradigm Shift for the Post-Pandemic AECO Industry. *Urban Science*, *6*. https://doi.org/10.3390/urbansci6040067

Meteora, Greece—Download Free 3D model by Fotis Giagkas (@fogiagas). (2018). Retrieved from https://sketchfab.com/models/816105d6666843369c1af8e5427e56cf/embed?autostart=1

Mohammadi, N., & Taylor, J. E. (n.d.). *Devising a Game Theoretic Approach to Enable Smart City Digital Twin Analytics*.

Nehab, D., Barczak, J., & Sander, P. (2006). *Triangle order optimization for graphics hardware computation culling* (Vol. 2006, p. 211). https://doi.org/10.1145/1111411.1111448

Ohori, K. A., Ledoux, H., Biljecki, F., & Stoter, J. (2015). Modeling a 3D City Model and Its Levels of Detail as a True 4D Model. *ISPRS International Journal of Geo-Information*, *4*(3), 1055–1075. https://doi.org/10.3390/ijgi4031055

Oyesode, S., Dare-Abel, O., & Daramola, S. (2022). *BIM Maturity Level of Architectural firm BIM Operators in Lagos State Nigeria*. https://doi.org/10.13140/RG.2.2.32219.44326

Palace of the Popes, Avignon, France—Download Free 3D model by Brian Trepanier (@CMBC). (2022). Retrieved from https://sketchfab.com/models/e4ee2e66d36242e3ba72e0627b8c61bf/embed?autostart=1

Park, S., Lee, S., Park, S., & Park, S. (2019). AI-Based Physical and Virtual Platform with 5-Layered Architecture for Sustainable Smart Energy City Development. *Sustainability*, *11*(16), 4479. https://doi.org/10.3390/su11164479

Pimentel, K. (2021). *Visualizing the invisible: The sound of real and virtual worlds*. Unreal Engine. Retrieved from https://www.unrealengine.com/en-US/spotlights/visualizing-the-invisible-the-sound-of-real-and-virtual-worlds

Prague Castle, Prague, Czech Republic—Download Free 3D model by Brian Trepanier (@CMBC). (2021). Retrieved from https://sketchfab.com/models/2de5f6d935b54da8b4fec2312e6f1f8e/embed?autostart=1

Rautenbach, V., Coltekin, A., & Coetzee, S. (2015). Exploring the Impact of Visual Complexity Levels in 3D City Models on the Accuracy of Individuals' Orientation and Cognitive Maps. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, *II-3/W5*, 499–506. https://doi.org/10.5194/isprsannals-II-3-W5-499-2015

Rosen, R., von Wichert, G., Lo, G., & Bettenhausen, K. D. (2015). About The Importance of Autonomy and Digital Twins for the Future of Manufacturing. *IFAC-PapersOnLine*, *48*(3), 567–572. https://doi.org/10.1016/j.ifacol.2015.06.141

Sacks, R., Koskela, L., Dave, B. A., & Owen, R. (2010). Interaction of Lean and Building Information Modeling in Construction. *Journal of Construction Engineering and Management*, *136*(9), 968.

Shiode, N. (2000). 3D urban models: Recent developments in the digital modelling of urban environments in three-dimensions. *GeoJournal*, *52*(3), 263–269. https://doi.org/10.1023/A:1014276309416

Singh, S. P., Jain, K., & Mandla, V. R. (2013). VIRTUAL 3D CITY MODELING: TECHNIQUES AND APPLICATIONS. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XL-2/W2*, 73–91. https://doi.org/10.5194/isprsarchives-XL-2-W2-73-2013

Smisek, P. (2018). *Creating a Digital Twin of Hungarian State Opera*. Unreal Engine. Retrieved from https://www.theb1m.com/video/creating-a-digital-twin-of-hungarian-state-opera

Somanath, S., Naserentin, V., Eleftheriou, O., Sjölie, D., Wästberg, B. S., & Logg, A. (2023, May 3). *On procedural urban digital twin generation and visualization of large scale data*. arXiv. Retrieved from http://arxiv.org/abs/2305.02242

Southern District Police Station—Download Free 3D model by Katie Wolfe (@katiewolfe). (2022). Retrieved from https://sketchfab.com/models/3353cf5bfbda4b8797e845594b0cbfa7/embed?autostart=1

Strzalka, A., Monien, D., Koukofikis, A., & Eicker, U. (2015). *Sensitivity analysis for minimization of input data for urban scale heat demand forecasting.*

Suwalki, Railway station—Download Free 3D model by zhenkoest (@zhenko). (2022). Retrieved from https://sketchfab.com/models/fde37c67c5854973ab2d546bf446d672/embed?autostart=1

Tekinerdogan, B., & Köksal, Ö. (2018). Pattern Based Integration of Internet of Things Systems. In D. Georgakopoulos & L.-J. Zhang (Eds.), *Internet of Things – ICIOT 2018* (pp. 19–33). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-94370-1_2

Times Square, New York City, NY, USA - Download Free 3D model by Brian Trepanier (@CMBC). (2021). Retrieved from https://sketchfab.com/models/b1cf32ba3cf040bca21900fdfed71562/embed?autostart=1

Turner, A. (2006). *Introduction to neogeography* (First). O'Reilly.

van Winden, W., & de Carvalho, L. (2017, November). *Cities and digitalization: How digitalization changes cities - innovation for the urban economy of tomorrow*. 1–24.

Verhoef, P. C., Broekhuizen, T., Bart, Y., Bhattacharya, A., Qi Dong, J., Fabian, N., & Haenlein, M. (2021). Digital transformation: A multidisciplinary reflection and research agenda. *Journal of Business Research*, *122*, 889–901. https://doi.org/10.1016/j.jbusres.2019.09.022

Vial, G. (2019). Understanding digital transformation: A review and a research agenda. *The Journal of Strategic Information Systems*, *28*(2), 118–144. https://doi.org/10.1016/j.jsis.2019.01.003

Wan, L., Nochta, T., & Schooling, J. (2019). *Developing a City-Level Digital Twin – Propositions and a Case Study* (p. 194). https://doi.org/10.1680/icsic.64669.187

White, G., Zink, A., Codecà, L., & Clarke, S. (2021). A digital twin smart city for citizen feedback. *Cities*, *110*. https://doi.org/10.1016/j.cities.2020.103064

Ying, Y., Koeva, M., Kuffer, M., & Zevenbergen, J. (2023). Toward 3D Property Valuation—A Review of Urban 3D Modelling Methods for Digital Twin Creation. *ISPRS International Journal of Geo-Information*, *12*(1), 2. https://doi.org/10.3390/ijgi12010002

Zhu, Q., Hu, M., Zhang, Y., & Du, Z. (2009). Research and practice in three-dimensional city modeling. *Geo-Spatial Information Science*, *12*(1), 18–24. https://doi.org/10.1007/s11806-009-0195-z

Zlatanova, S. (2000). *3D GIS for urban development*.

Институт физкультуры, Краснодар (КГУФКСТ)—Download Free 3D model by Mikhail Volkov (@mgv). (2021). Retrieved from https://sketchfab.com/models/95060fad89534758a84887552e9e9320/embed?autostart=1