Geographical Information Management and Applications

Maintaining an up to date digital twin by direct use of point cloud data

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Abstract

Within the context of smart cities and internet of things the need for managing all data flows and processes within a city is growing. It is within these developments that the concept of digital twins is increasingly being applied by city governments to provide a single platform that allows for doing so. Although a digital twin provides numerous amounts of functionalities, a 3D geometric model is essential for representing the city as it is. As one of the key characteristics of digital twins are that they reflect the real world as truthful and up to date as possible, it is necessary for the 3D model to be as up to date as well. Generally the development of 3D city models requires several processing and modelling steps. Considering cities are constantly changing, a once created 3D model can already be outdated by the time it is finished. Following recent technological advancements and innovations, the use of LiDAR and photogrammetry has become rather popular in generating 3D point clouds of physical environments. Besides being able to represent the real world in a very detailed way, one of the most beneficial characteristics is that point clouds lend themselves for direct usage. This means a 3D point cloud can be used directly as the 3D geometric model for a digital twin, without the need for further processing steps. In order to update the 3D geometric model, only changed areas in the city have to be re-scanned, followed by change detection operations that provide a point cloud of those objects within a city that have changed. The frequency in which this is executed depends on the intended use of the digital twin. Whereas most digital twins aim at real-time data representation, this is practically impossible without constantly monitoring whole cities. However, contemporary sensing and measuring technologies can aid this process.

Abbreviations

2D	Two-dimensional
3D	Three-dimensional
AEC	Architecture, Engineering & Construction
ALS	Airborne Laser Scanning
BAG	'Basisregistratie Adressen & Gebouwen' (Key Registration Addresses & Buildings)
BGT	'Basisregistratie Grootschalige Topografie' (Key Registration Large-Scale Topography)
BRO	'Basisregistratie Ondergrond' (Key registration subsurface)
CAD	Computer-aided Design
BIM	Building Information Modelling
DEM	Digital Elevation Model
DSM	Digital Surface Model
DT	Digital Twin
DTM	Digital Terrain Model
IoT	Internet of Things
LiDAR	Light Detection and Ranging
LoD	Level of Detail
MLS	Mobile Laser Scanning
TLS	Terrestrial Laser Scanning

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1. Introduction

This chapter will cover a brief introduction to the overall topic of this research, including a part on the context in which the research is executed as well as the problem statement and research objectives. Also, the relevance of this research will be addressed followed by an overview of Dutch digital twin examples.

1.1 Context & background

Currently, already more than half of the world's population is living in urban areas and this amount is continuing to grow as it is expected that, by 2050, more than two-third of the earth's inhabitants will be living in cities (Cassandras, 2016). Besides cities becoming busier and more populated, an increase in sensing and monitoring devices throughout cities can be noticed as well. Not only stationary sensors and cameras grow in numbers but also vehicles are increasingly equipped with all sorts of sensing devices. All these devices produce enormous amounts of data, causing data flows within cities to reach an all-time high (Psychogyiou, 2017). As the generation and collection of data has become easier and more accessible while technological advancements and digitalization keep increasing, the demand for adequate and accurate management of all this data has grown.

Following these developments, the concept of 'Smart City' has been increasingly adopted by cities throughout the world, while related developments as ´Internet of Things´ (IoT) is gaining popularity as well. Besides, all sorts of new technologies and digital advancements such as smart phones, sensors and cloud services affect the way in which these concepts are being shaped. In general, a network of sensors situated throughout the city forms the basis of the technological infrastructure smart cities rely on (Cassandras, 2016). These sensors can have all sorts of purposes, varying from monitoring traffic conditions to measuring air quality. Besides, connection to the internet is required for the sensors to interact with all sorts of wireless devices, as well as for cloud-services to gather and store the collected data. Although there is no single definition of a smart city, consensus on what comprises a smart city can be derived from a variety of definitions originating from different perspectives. As Cassandras (2016) recites, the following elements can be attributed to a smart city: sensible, connectable, accessible, ubiquitous, sociable, sharable and visible.

Nevertheless, different projects being executed as a smart city project are not always aligned with each other, causing these projects to be rather stand-alone smart city projects while lacking integration and interconnection. As these projects usually focus on specific parts of a city or on specific sensor data, lots of these projects run parallel to each other. To overcome this fragmentation and assist in managing all the processes accompanying these developments, the concept of digital twin has gained interest for usage within urban development contexts. The use of digital twin has roots in several fields of interest as it is known to be a unique way of representing the real world, or at least parts of it, digitally. Although initially a digital twin is merely a digital replica of a real world entity, object or process, there is not a prescribed form in which this is being represented. In general, however, some type of 3D representation forms the basis for a digital twin, especially when being used for city related purposes. In line with recent developments regarding the growing interest in and usage of 3D data, the demand for high quality, detailed 3D representations is increasing. Besides, technological possibilities keep on advancing, thereby benefitting the way in which these 3D representations can be used.

In order to obtain a 3D representation that fits the requirements of its intended usage, a variety of methods for 3D extraction or 3D modelling exist. Whereas these methods vary in how a 3D representation is achieved, so does the accuracy in which reality is represented. One of those methods for digitally representing reality in 3D is by the use of point cloud data, which has recently gained more and more attention as laser scanning and dense image matching techniques have become more accessible while computer power keeps increasing, causing point cloud data to be handled much easier than before. Furthermore, point clouds are able to reflect the real world in a very detailed, photorealistic way without the need for extra processing and modelling, thereby allowing for direct usage.

There are several additional advantages related to the direct use of point cloud data, especially for digital 3D representations. However, these advantages have only been researched until recently. Besides, the body of research dedicated to the direct use of point cloud data in relation to its application in contemporary digital twin cities is rather limited.

In order to give further understanding of the topics addressed in this research and provide extra background information about the context in which this research will be executed, the main topics will be briefly elaborated on in the following paragraphs.

Digital twins

Cities increasingly aspire a construction in which all processes and data streams can be managed in an efficient and structured way. A city itself can, in some way, even be seen as a collection of processes and data streams. It is within this aspiration that an increasing amount of cities in fact create a digital duplication of their city through which management of these processes and data streams can be achieved.

Such a digital duplicate is generally called a digital twin (DT) or, more specifically, a digital twin city. For city governments, a digital twin can be used for several purposes. On one hand it can contribute to gain new insights or uncover previously unnoticed processes. On the other hand digital twins can be used to provide new or improve existing services to its residents. Hereby benefits of having a digital twin lie within the opportunities of gaining insights in all sorts of aspects and processes within the city, like air pollution, noise disturbance, traffic congestions and public safety, to name a few.

From a more theoretical perspective, as Qi et al. (2019) state, a digital twin provides a unique way of reflecting a physical entity in the digital world, especially regarding its shape, position, gesture, status and motion. They hereby explain that a digital twin can be used for monitoring, diagnostics, prognostics and optimization with regard to sensory data acquisition, big data analytics, artificial intelligence and machine learning. Moreover, it should be stated that the application of digital twins is not limited to the context of cities alone. In fact, cities are only one of the many application fields in which digital twins are being deployed. An overview of these application fields is presented in Figure 1.

Within these different areas, digital twin concepts are widely applied for a variety of purposes, varying from governments with a general interest, to private sector companies and industries with business specific needs. Hereby, the way the digital twin is designed can vary as well, as it is possible to create a digital twin for almost every thinkable real-world object, organisation, process or product, given it is a functional digital representation of reality. Nevertheless, the majority of contemporary digital twins are designed as, or based on, a 3D representation.

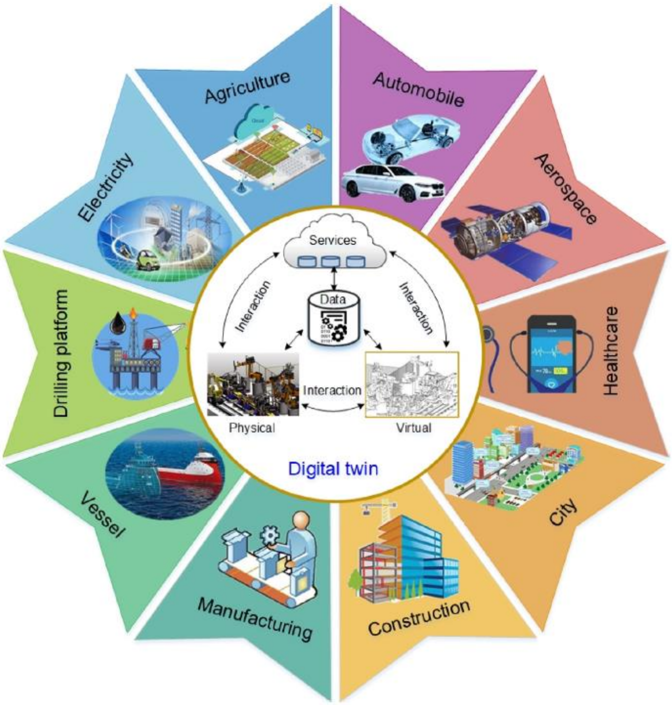


Figure 1 – Application fields of digital twin (Source: Qi et al., 2019)

Although in principle a digital twin does not require a 3D model, it does help with understanding and interpreting the subject of interest as it is. Besides, it makes sense to represent the actual three-dimensional world in a 3D digital environment, especially if the purpose of a digital twin is to replicate a city. Hereby a three-dimensional geometric model is often used as basis for the digital twin, representing the buildings and infrastructure of that city. Yet, in principle, a 3D representation in itself cannot be considered a digital twin, as the added value of a digital twin lies within extra functionalities besides just being a visual representation. Connecting a city's processes and data streams to the 3D representation is essential, which allow for detailed insights in how these are related. In other words, information about the digital twin's real-world subject needs to be part of the 3D representation in order to enhance its functionality as a digital twin, rather than a visual 3D representation. This means that, besides creating a 3D representation, it needs to allow for linkage to, or enrichment by additional data and information inherent to the subject it represents.

3D representation: Point clouds

For a lot of purposes, a relatively simple, low-quality 3D representation of a city will suffice for achieving the desired functionalities. However, current advancements in 3D modelling and visualization techniques, as well as 3D data collection have significantly reduced the time and cost aspects of creating a detailed, high resolution 3D city representation. These techniques can be based on several types of data, of which point cloud data is one that is increasingly being used to represent the as-is environment in 3D (Wang & Kim, 2015). Figure 2 provides an impression of a coloured point cloud (Discher et al., 2019). Although it is no stated which method has been used to generate the point cloud, it does provide a very realistic representation.

Figure 2 – Impression of a coloured 3D point cloud (Source: Discher et al., 2019)

Point cloud data has several beneficial characteristics compared to rather traditional raster or vector data types as they generally provide more detail. The high point density allows for precise, accurate and high quality analyses. Furthermore, they allow for quick selection and visualization of specific points and are able to be well organised on different levels of detail (LoD) (Zhang et al., 2017). However, it can be argued that one of the most valuable benefits of point cloud data is that it allows for direct usage. This means extra processing or modelling steps, for example, can be left out in creating a 3D representation. By doing so, both time and costs can be saved as several procedures between data acquisition and delivering the 3D model will not be necessary. The resulting 3D representation will be the raw point cloud, minimally processed to provide a clean, detailed and functional representation of reality.

Acquisition of point cloud data, however, can be done through several methods of which photogrammetry techniques such as dense image matching and laser scanning and ranging techniques are most common. In recent years, the most common way of acquiring point cloud data has been by using Light Detection and Ranging (LiDAR) scanners. Led by technological advancements and innovations in specialised, high-tech equipment, the commercial availability of these scanners has rapidly increased. As a result, collecting point cloud data of a physical three-dimensional environment has become more accessible and resulted in laser scanning techniques becoming the dominant technology for 3D data capturing (Remondino et al., 2014).

In general, a distinction is made between two common uses of LiDAR scanners. Ones that are used to scan an object or environment from the air are classified as airborne laser scanners (ALS) and can be mounted on drones, helicopters and airplanes. The second type concerns scanning an object or environment from ground level, and is classified as either a terrestrial laser scanner (TLS) or as a mobile laser scanner (MLS), depending on whether the laser scanner is mounted on a static (TLS) or a dynamic (MLS) object or vehicle. Especially for generating point clouds of urban environments, mobile laser scanners have gained popularity as they can be mounted on all sorts of objects and vehicles, varying from motorcycles and cars to bicycles and backpacks. By doing so, it provides a relatively quick and easy way of scanning large and complex areas (Rodríguez-González et al., 2017), while allowing for fast, uncomplicated and even automatic data collection (Grasso et al., 2017).

Photogrammetry techniques, on the other hand, are regaining popularity due to advancements and new developments in both hardware and algorithms, as Remondino et al. (2014) address. In the basis, photogrammetry relies on image matching methods, through which 3D geometry is obtained by creating images of the same object or area from different perspectives (Kodde, 2016). The principle is shown in Figure 3.

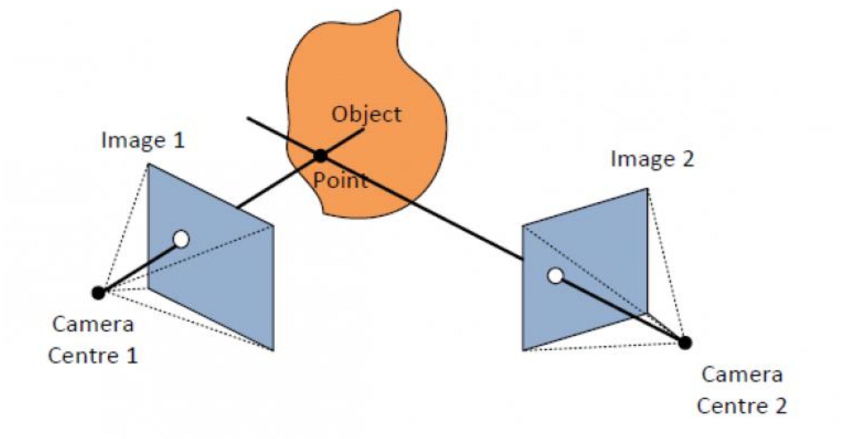


Figure 3 – Principle of image matching (Kodde, 2016)

This process is generally carried out automatically by the use of algorithms. As Ali-Sisto & Packalen (2017) explain, two or more overlapping images are needed for an algorithm to generate 3D geometry. Based on cross correlation between two or more overlapping images showing the same object while knowing the orientation of the images, height information can be determined. If this process is repeated for each pixel within the images, a 3D point cloud can be created. An advantage of using dense image matching over LiDAR when generating point cloud data, is that colour attributes are automatically stored within the points, thereby directly providing a photorealistic representation of reality, both in terms of geometry as in terms of RGB values.

Change detection and updating

Direct usage of a point cloud provides several functionalities, which are beneficial for its use in digital twins. As the point cloud itself is used as the 3D representation, it is not just an intermediate datatype for a different kind of 3D product. The absence of a product relying on the point cloud data makes that the 3D representation is more dynamic in its usage, as changes can be applied almost directly on the final product. In line with the dynamic nature of point cloud data is the versatility of modern cameras and LiDAR systems, MLS in particular, which enhance the easy collection of data in urban environments, especially if these environments change over time. This aspect is important since change is inherent to cities. As cities are ever evolving, developing and changing on all sorts of aspects, the 3D representation needs to do so as well.

These changes include all adjustments to the physical environment, such as the construction of new or changes to existing buildings and infrastructure. All these developments have influence on the state of the physical environment, which means a 3D representation of that environment needs to be updated according to these changes, in order to remain a truthful representation of the real world. This is necessary to prevent the 3D representation from becoming outdated and lose any utility value.

Not every change in the physical environment, however, necessarily means a significant change. Therefore, certain considerations are required on when a change is significant enough in terms of magnitude, impact or relevance.

Nevertheless, changes in the physical environment must be detected prior to being updated to existing the 3D representation. Detecting change in an urban environment takes time and effort, considering that the changes need to be recognized before being detected, analysed and updated. Since re-scanning an entire city in high detail in search for possible changes requires a lot of work, it can be more efficient to only (re-)scan those areas in which change has occurred. This enhances selective updating, thereby saving time and effort as well as storage capacity (Richter & Döllner, 2014). However, modern techniques increasingly allow for automation in several processes regarding detection of change, as well as classification of objects and the eventual process of keeping the digital twin up to date.

Enriched point clouds

Within the field of 3D change detection, point clouds are increasingly considered useful. One of the features on which change detection can be based is by the use of object recognition or classification.

In itself, a point cloud is nothing more than a collection of points containing an X, Y and Z coordinate. Several standard attributes can be assigned to those points, such as RGB values for realistic colouring. In the case of point clouds acquired through LiDAR scanners, additional photographs are needed to provide RGB information. By simultaneously capturing point cloud data and imagery, points can be easily assigned a colour. Photogrammetry based point clouds, however, already possess RGB information since they are generated based on imagery.

Several other forms of data and information can be assigned to, integrated in or linked to the points in a point cloud. This process can be defined as semantical enrichment, as points within the point cloud are given meaning within the context of its usage. General semantic enrichment of point clouds involves the classification of objects within the point cloud, meaning that groups of points representing a certain object are assigned the same classification. As this process can be extended towards all sorts of enrichment, the point cloud becomes smart in the sense that it can distinguish points, or groups of points, based on certain characteristics. Also this process is a contemporary topic of research in which possibilities of automation are of high interest.

In respect to 3D change detection, point clouds are considered especially useful. The nature of point clouds makes them especially useful for object recognition and classification (Velizhev et al., 2012; Hu et al., 2013; Che et al., 2019). Object recognition can be of high value when performing change detection, and offers possibilities for all sorts of analysis purposes, of which those concerned with semantics are of great interest. An increasing body of research is dedicated to semantically enrichment of point clouds, as a point cloud itself does not inherently contain any semantic information (Stojanovic et al. 2018, Stojanovic et al., 2019; Che et al., 2019). Methods regarding semantic enrichment of point clouds range from manual classification to (semi-)automatic image-based and machine learning methods. Manual methods, however, require certain skills and knowledge, apart from being time consuming. From this perspective, Poux et al. (2016) propose a point cloud structure that is more intelligent and does not rely on interpolation methods. Within this 'smart point cloud' structure both 3D point data as well as semantics and topology are integrated.

1.2 Problem definition

Multiple problems and corresponding challenges can be identified when creating and maintaining a digital twin based on point cloud data. The first problem lies within the starting situation. As the digital twin has to be created at some point, the 3D representation imitates the state of the physical environment at a certain point in time. This means that the 3D representation, and thereby the digital twin, only reflects a snapshot of reality. Depending on the intended use of the digital twin, choices need to be made regarding this starting situation, being when and where to start. The challenge lies in obtaining a 3D representation that is as complete as possible and allows for future changes and updates, as well as fulfils the functional requirements of the digital twin. Given that cities are more than just infrastructure and buildings, choices need to be made regarding which objects are initially included and which are excluded. All these challenges require choices on how the data is collected and processed in order to provide the most suitable starting situation.

The second problem lies within the way in which changes in the physical environment are being detected, as well as how these changes are being applied to the digital twin. As the digital twin is, in some way, already outdated after the first changes in the physical environment have occurred, it is necessary to detect these changes and apply these to the digital twin. The challenge lies within finding the optimal balance between efficiency and quality of the change detection. Hereby choices need to be made with regard to finding the optimal balance between efficiency and quality of the change detection, while taking into account at which point a change is considered final, as changes are mostly part of a process. Additionally, the changes need to be recognized, detected and validated. The challenge herein lies within finding the most efficient, though sufficient methods to go through these processes.

The third problem lies within updating the geometrical model of the digital twin, and keeping it up to date. Changes in the real-world need to be recognized, detected and validated before being updated to the digital twin. As having a digital representation of the real world is one thing, keeping it up to date with current and future developments is where utility value can be increased. As cities are ever developing and evolving, detecting change and updating these changes should be a dynamic and ongoing process. The challenge is to accurately identify and scan the changes, after which the digital twin needs to be properly adjusted in line with the changes. Moreover, choices need to be made regarding storage of the data and documentation of previous situations.

As part of the third problem, a fourth problem can be identified considering the frequency in which changes are detected, as well as the frequency in which the digital twin is updated. Changes occur on an irregular basis and unsystematic. Besides, in some cases it can be desirable that data is only recaptured of actually changed objects, instead of recapturing data of a whole area, before being updated to the digital twin. The challenge lies within finding the most favourable frequencies concerning change detection and updating the digital twin, which do not necessarily have to be the same. Also within this challenge, considerations regarding the efficiency and quality of change detection and updating the digital twin are of importance since they may influence both the possible as well as the desired frequencies.

1.3 Research objectives

The overall objective of this research will be to gain insights in the extent in which point cloud data can be directly used for representing and maintaining a digital twin, as well as the practical implications regarding these processes. More specifically, the objective is to provide an understanding of the current situation regarding digital twins in the Netherlands, while taking into account ongoing developments, both nationally and internationally. As is addressed in the problem statement, several problems and challenges can be identified. As a result, the objectives of this research will follow from these challenges.

The first objective is to provide an overview of existing methods and considerations of creating a digital twin based on the direct use of point cloud data, in order to attain a complete and detailed representation of the physical environment. The focus will be on the point cloud as the representation itself, instead of being an intermediate product for creating a 3D representation. To achieve this, the aim is to formulate basic requirements of such a representation in order to function as a digital twin, as well as to show how these basic requirements can be implemented in a prototype digital twin.

The second objective is to gain insights in the methods regarding the use of point cloud data for detecting change in the physical environment and in order to update these changes to the digital twin. Furthermore, the aim is to recognize the most suitable methods regarding the practical implications of change detection and updating of the digital twin.

The third objective is to provide a strategy on the frequency of detecting and updating changes in the built environment to the digital twin, based on the methods for creating the digital twin, detecting change and the way of keeping it up to date.

Research questions

Following from the problem statement and the research objectives, the central question of this research will be:

To what extent can point cloud data be used directly in order to act as an up-to-date digital twin?

Subsequently, the main question will be accompanied by sub-questions. Answering these will contribute to providing an answer on the main question. The sub-questions will be the following:

- *To what extent can a point cloud be used to directly represent a digital twin?*
- *To what extent can point cloud data be used for change detection in a physical environment?*
- *What are the practical implications regarding change detection and frequencies for updating the digital twin?*

1.4 Scope

Defining the scope of this research will aid to keep the research within set boundaries, without neglecting relevant topics. Hereby, a distinction will be made between what is in scope and what is out of scope of this research.

In scope

The scope of this research will be defined based on the main topics this research addresses, being point cloud data and its usage in digital twin cities.

First of all, the context in which this research is executed is derived from developments regarding the concepts of smart city and internet of things. It is in line with these developments and within this context that the concept of digital twin will be addressed. Although the concept of digital twin can be used in a much broader way, this research will limit its focus towards the usage of digital twin within an urban context in which the concept of digital twin will be treated as a digital duplicate of a city. Hence, terms as digital twin, digital twin city and twin city will be used as synonyms.

Within these boundaries, the main requirement of the digital twin is that it is represented by or based on a 3D city model. Since there are a lot of methods and techniques with which a 3D city model can be derived, it is impossible to compare or assess all of them. Although developments regarding acquisition, processing and usage of 3D data are being discussed and commonly used methods will be addressed, the focus of this research will be on the use of point cloud data for this purpose. More specifically, the main objective is to explore the possibilities of direct usage of LiDAR point cloud data as 3D representation for a digital twin.

As the developments regarding point cloud 3d modelling and digital twinning are of international proportions, examples of these developments are endless. However, projects regarding these developments in the Netherlands are gaining more and more interest. As these concepts are being implemented more frequently by both governments and private companies in a variety of application fields, this research tries to focus as much as possible on the Dutch context. Nevertheless, outcomes of this research may be applicable to situations internationally.

Out of scope

Besides defining what is in scope of this research, it is also important mentioning what is out of scope. Whereas a physical environment changes on more aspects than just the built environment, all other than these (e.g. temperature, traffic, air quality) are not part of this research. In addition, indoor environments will not be included in this research, although work regarding indoor point cloud representations is considered relevant.

As direct use of point clouds is a central topic, conversion or interpolation of point clouds are regarded out of scope, although being processes that are relevant to address. Furthermore, as technical aspects regarding semantics, classification and object recognition are subjects that are related to this research, they are not extensively researched. Briefly addressing existing work on these topics will suffice.

Practical application

In order to provide this research with certain directions, actual scenarios in which digital twins can provide added value will be addressed. Hereby, existing scenarios and practical examples will be discussed. Applying this research to these existing scenarios and practical examples will help concretise the findings and support its relevance. Although the development of digital twin cities in general involve at least the creation of a 3D representation of that city, the application field in which the digital twin is being implemented dictates which data and information is relevant to include in the representation. Vegetation management, infrastructure maintenance and construction monitoring are possible application fields to address. However, there still need to be basic requirements that transcend the variety in application fields and thus provide a framework describing the minimal features of a general digital twin city.

1.5 Relevance

Representing the world in 3D is increasingly becoming the standard when modelling real-world objects, systems and processes. Besides, the ongoing technological advancements in 3D modelling and data management enhance the possibilities for 3D applications.

In line with Smart City developments and IoT implementations, the concept of digital twin has gained a growing amount of interest from both the academic and the business world whereas 3D city modelling is an ever growing field of research. Developments regarding 3D modelling can be seen in the applications of Computer-aided Design (CAD) and Building Information Modelling (BIM), while commercial availability of high quality laser scanners enhanced the (direct) usage of point cloud data.

Examples of the growing interest in digital twins can be seen both in the business world as well as local and national governments. As cities are increasingly being monitored, considering the amount visible and non-visible sensors is continuing to grow, digital twins provide a modern yet functional way of managing all these different kinds of data. Furthermore, as applications of digital twins are endless, exploring new possibilities that fit within societal needs can be explored.

On a scientific level, this research will attempt to add to the existing body of knowledge concerning practical implications of maintaining an up to date digital twin with regard to the 3D city model and the changing physical environment it is representing. As the built environment is ever evolving and digital representations are becoming increasingly realistic, the demand for accurate representations is growing as well. Moreover, the research field on direct use of point clouds has gained interest since only recently, whereas direct point cloud usage for updating the 3D model of a digital twin is rather new.

1.6 Conceptual model

The essence of this research is conceptualized and deducted to the most essential objectives. As discussed, the context in which this research will be executed is based on the current Dutch situation regarding DT development and smart city approaches. The focus of this research will be on the 3D model representing the physical world in the digital twin.

The method proposed within this research directly uses point cloud data as the 3D geometric model. As the physical world changes over time, the digital twin as to updated accordingly. With regard to the 3D geometric model this means that changes in the real world need to be detected and updated to the digital twin, which is a dynamic process. This process is seen within the red circle in Figure 4.

This conceptual model is partly based on the DT conceptual model as presented by Modoni et al. (2019), although adjusted in line with this research.

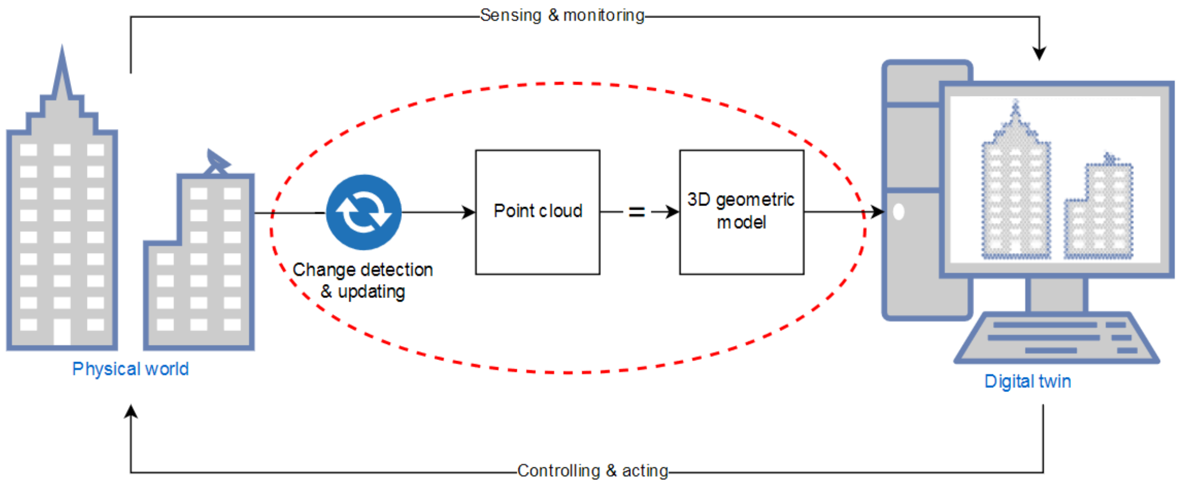


Figure 4 – Conceptual model (Modoni et al., 2019, adjusted)

1.7 Dutch context

As this research mainly focuses on the current situation as well as the future possibilities of point cloud usage and digital twin development in the Netherlands, this paragraph will provide an overview of several initiatives, projects and practical examples regarding these topics. The extent of these initiatives varies from explorative intentions to functional digital twins.

It can be said that 3D is becoming the new standard in visualising and representing reality, leading to increasing interest coming from both businesses and the industrial sector as well as governments and semi-governmental organizations. Hereby LiDAR and aerial photography are of great value since they provide detailed 3D information in the form of point clouds. Also in the Netherlands, the trend towards the development of 3D city models and digital twins has found its way. Increasing computer power and ongoing software development enhance the efficiency in processing and analysis processes of three-dimensional data. This leads to 3D data increasingly being used for representing reality in a digital or virtual environment as methods for 3D data collection are becoming more advanced and accessible. On the same time, point clouds data is increasingly being used as basis for 3D representations and digital twins. Within the Netherlands, for example, one of the main sources for 3D data is the AHN.

Considering the current state of the Netherlands regarding digital twins, it stands out that most initiatives arise within the context of smart cities. Since the advancements in digitalization and the accessibility of 3D data have grown, applications like digital twins have gained interest in smart city developments. As is stated by De Vries (in Koops, 2019), digitalization is an important method to substantiate the plans of smart cities. Thereby digital twins can be used to make information accessible to the right people at the right time, within an interesting and usable environment.

Besides, it can be noticed that several methods in obtaining a 3D model of reality are used, varying from gaming environments to combining BIM, GIS and point cloud data. This shows that there is not a single, standardised way in which digital twins are approached in the Netherlands, especially in creating and depicting the real world in 3D. However, the relevance and challenges of the increasing popularity of 3D is seen by both governments and companies.

As De Groot (2019) states, information shown by a 3D model is automatically assigned a higher 'reality' value when 3D visualizations are perceived as more 'real'. He addresses the challenge lies in keeping the 3D experience as close to reality as possible. In terms of digital twins, this means a one-time upload will result in an outdated model if nothing is done afterwards. By integrating sensors and their output data within a 3D environment, actuality can be incorporated, thereby creating a functional, up to date digital twin. However, as is rightfully stressed, the ´twin´ status can only be kept by keeping it up to date with reality.

Governmental initiatives

A national development in which the Dutch government is exploring the use of digital twins is the implementation of the Environment and Planning Act (Dutch: 'Omgevingswet'). A report by Capgemini states that the growing amount of modern sensors as well as their output contribute to a whole new virtual world (Takken, 2017). These sensors enable the developments of digital twins for real-time monitoring of objects and their performance. However, especially for government products, priority is given to usability, as not only expert users are part of the target audience. Within this context, digital twins can be used by the government to improve and develop new services for companies and inhabitants.

Progressions towards the use digital twins by the Dutch government are visible in collaborations between multiple (semi-)governmental stakeholders like Kadaster, the Association of Dutch Municipalities (VNG) and the Dutch BIM-Loket (Corstens et al., 2019). Hereby three pilots were introduced concerning the use of BIM within Dutch municipalities. The goal of these pilots is to integrate BIM in a variety of processes in which information concerning the physical world is used digitally, thereby improving business operations, providing services, policy making and execution and sustainability. Added value is seen in using BIM as an important contribution for digital twinning, especially concerning the current situation regarding usage of 3D information within municipalities. Digitalization of buildings is mostly done manually, while information is shared by a variety of stakeholders in a variety of formats. Not all municipalities accept the same formats, leading to rich 3D models being 'downgraded' to two-dimensional blueprints.

In order to provide insight in how these intentions should be worked out in practice, the VNG and BIM-Loket have published a roadmap showing the necessary input for a digital twin (Figure 5).

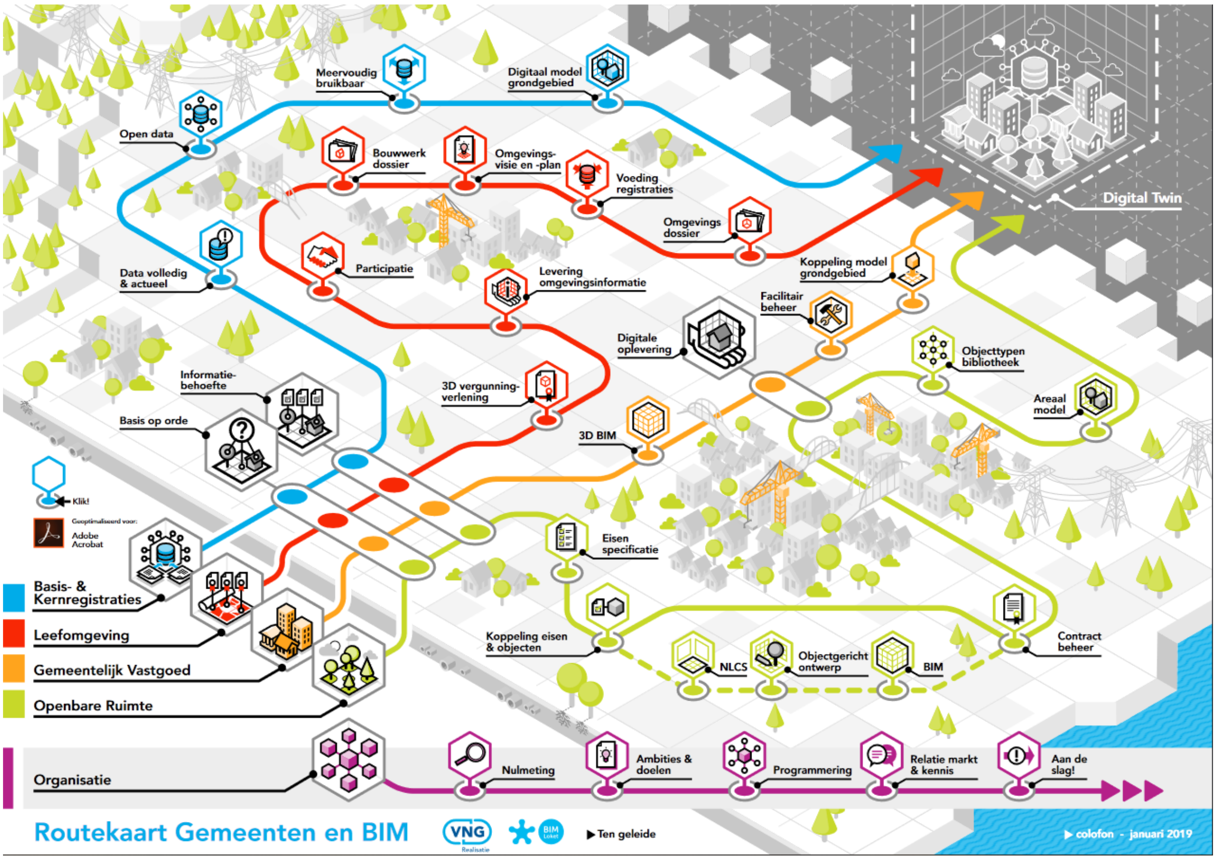


Figure 5 – Roadmap towards BIM for municipalities (Source: Bimloket, 2019)

Although the roadmap seems quite extensive, the essence is to make the transition from 2D-GIS to 3D-GIS. Hereby the aim is to create a 3D BIM model of the buildings, after which key registrations and relevant databases are directly linked to this 3D model, resulting in a digital twin.

Furthermore, initiated by Geonovum together with several Dutch governmental organisations, is the development of a national digital twin infrastructure for the physical living environment. A recently published investment proposal underlines the serious intentions regarding these developments. Within the contexts of energy, infrastructure, mobility, housing, agriculture and climate, complex issues arrise regarding the limited availability of space in the Netherlands (Geonovum, 2021). The so called 'Digitale Tweeling van de Fysieke Leefomgeving' (DTFL) is considered to be part of the solution for overcoming the societal issues by providing an information basis in the form of a digital representation for both urban and rural environments, based on data, models and visualizations.

The goal of the DTFL is to 1) provide an equal informationposition, 2) provide insights, 3) aids in visualizing and simulating the physical world in 3D, 4) aids in decission making processes and 5) aids in efficient monitoring and maintenance of physical objects.

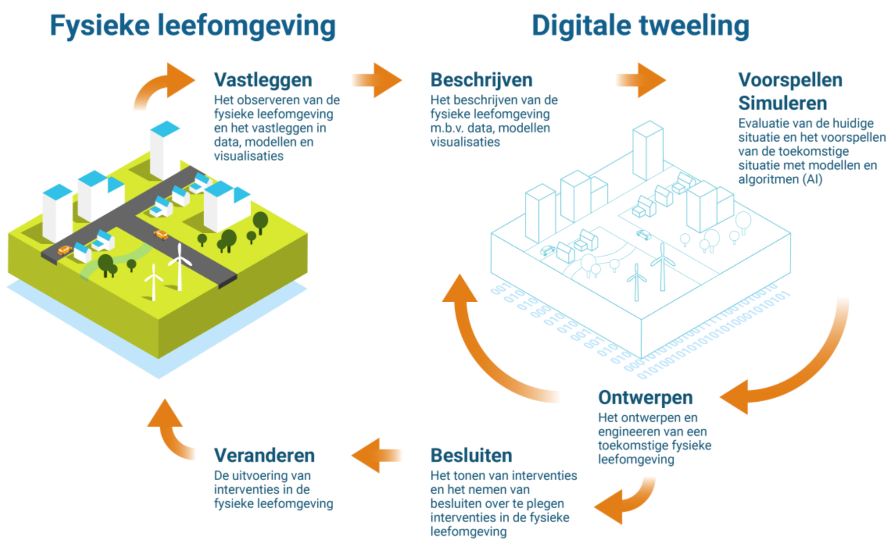


Figure 6 – Processes between the digital twin and the physical environment (Source: Geonovum)

Figure 6 shows the interaction between the physical world (*Fysieke leefomgevingl*) and the digital twin. The physical world is captured and described in the digital twin, which predicts and simulates current and future situations, after which design and decission processes lead to changes in the physical world.

Considering the data, the basis of this digital twin is formed by the national key registrations. These are supplemented by the use of aerial photography, LiDAR, satellite and sensor data. Moreover, including BIM-models is mentioned as example for integrating the 'geo-world' with the 'construction-world'. Moreover, the importance of standardization is mentioned. Based on the FAIR-principle, data should be findable, accessible, interoperable and reusable. Besides data standards, standards regarding models and visualizations and standards regarding development of the digital twin are deemed essential.

3D BAG

In the Netherlands, all information regarding buildings and addresses such as location, construction year and purpose of use, are incorporated in the ´Key Registration Addresses and Buildings´ (BAG). Although the Kadaster is responsible for maintenance, Dutch municipalities are responsible for delivering the data. In principle, however, the data is provided in 2D. This has changed with the release of 3D BAG, developed by the 3D Geoinformation Group as part of the Delft University of Technology.

In principle, one could identify the 3D key registration as some sort of digital twin, as spatial information regarding the physical environment can be viewed, queried and used within a three-dimensional environment. As stated on the website (3DBAG, 2021), the 3D BAG is an up-to-date data set in which 3D building models of the Netherlands are represented.

Hereby, 3D buildings are derived from combining two open data sets, being the 2D building data from the BAG dataset, and height data from the most recent AHN dataset, being AHN3. Based on a building's footprint, AHN data is used to determine its height after which the footprint is vertically extracted, resulting in a relatively basic representation. This is shown in Figure 7.

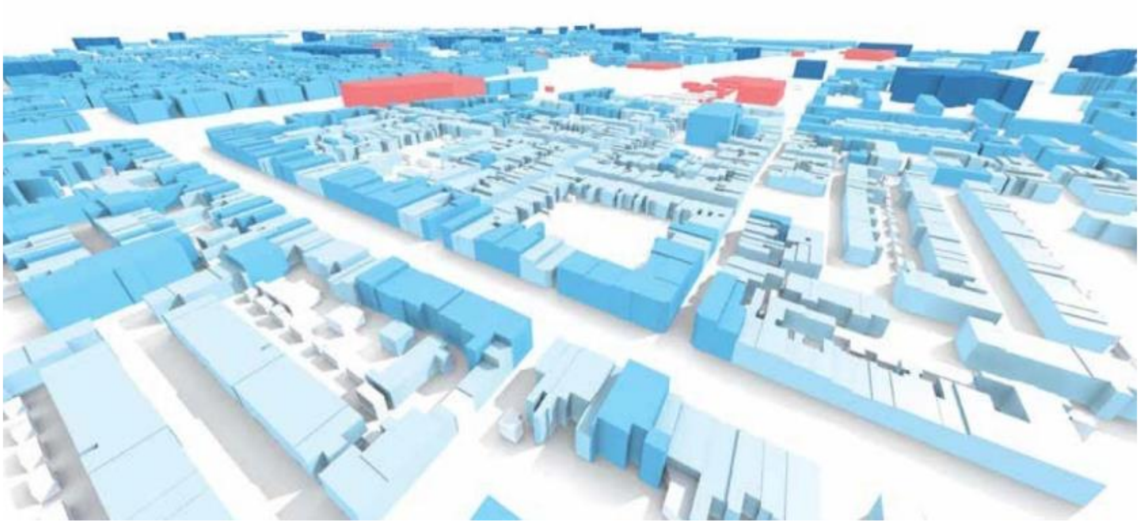


Figure 7 – 3D BAG impression (Source: Dukai et al., 2018)

Although not representing the world in a one-to-one realistic way, recent progressions and developments have led to the possibility of providing three levels of detail (LoD) within the 3D BAG viewer. Whereas LoD 1.2 and 1.3 provide low amounts of detail regarding both rooftops and facades, LoD 2.2 already shows more detail regarding rooftops. Facades, however, are still lacking detail. Moreover, buildings are represented as grey, square-like objects, thereby simplifying reality to a great extent. Nevertheless, the product can be considered functional as objects can be queried (Figure 8) and up to date to a certain extent. Whereas the key registration is regularly updated, the AHN3 data is captured between 2014 and 2019, meaning although the most recent data is used, it can still be already 7 years old depending on the year of acquisition.

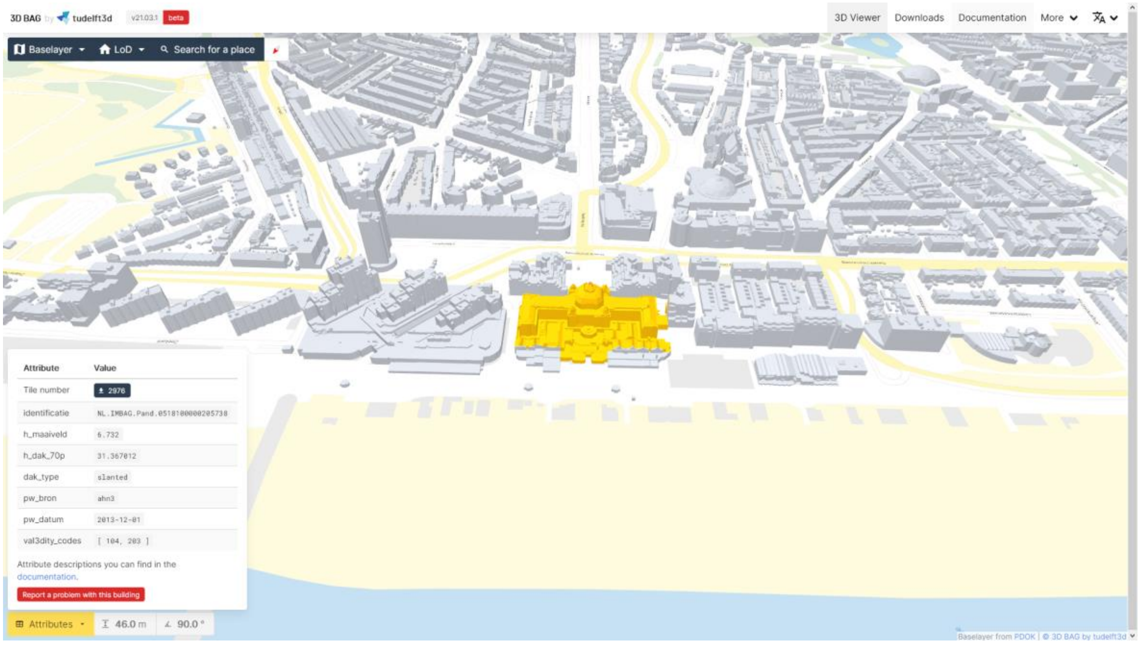


Figure 8 – Screenshot of 3DBAG in LoD2.2 (Source: 3DBAG, https://3dbag.nl/)

SPOTinfo

The digital twin developed by SPOTinfo provides access to combined, reliable spatial data of the whole of the Netherlands. Their so called 'Omgevingsserver' includes open data provided by the Dutch government and can be linked to organisation specific data and documents and real-time sensor data (SPOTinfo, 2020). Their aim is to provide easy access to cohesive spatial data at any time and anywhere. As they state, looking at an integral 3D map view as common reality creates insights. The data services provided through the ´Omgevingsserver´ are accessible from one source via open web services.

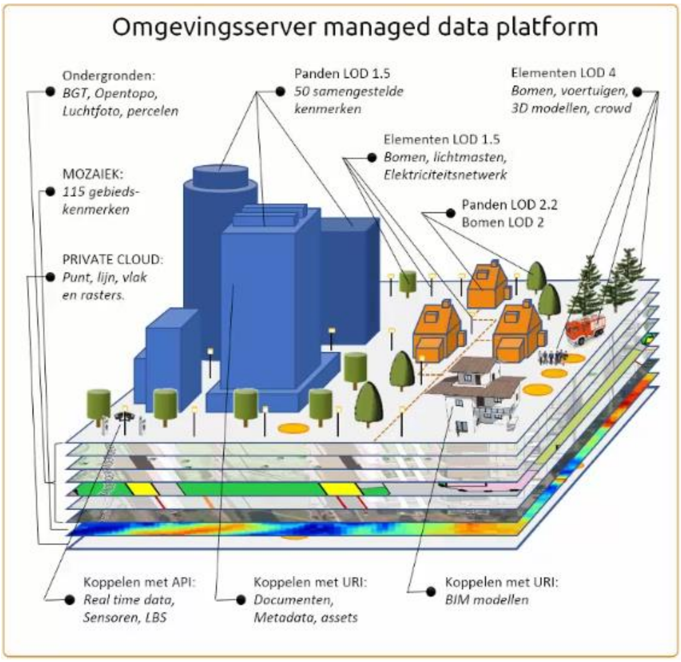


Figure 9 – Layout of the SPOTinfo digital twin (Source: Spotinfo)

As Figure 9 shows, the base layers are based on key registrations such as BGT, arial photos and provide vector and raster characteristics. Buildings and objects are represented in 3D in different levels of detail. Linking the objects and underlying datasets with real time data, sensor data, specific documents and BIM models, for instance, creates a digital twin for data driven decision making.

Hereby, as stated by SPOTinfo (2020), the digital twin provides the following functionalities:

- Access to cohesive integral datasets in more than 260 themes
- 2D and 3D objects, linked to 50 composed building characteristics
- Real-time data services
- Data-hub for managing organisation specific geo-data within a private cloud environment

Argaleo

Argaleo is a Dutch company that provides ICT services, applications and support to companies and governments. Their main product is called ´DIGITWIN´, which is a 3D web-application. Within this online tool, information from more than 200 data sources is incorporated varying from construction years of buildings to real-time train locations (BIGnieuws, 2019). This results in a nation-wide digital twin that, as stated by Argaleo (2021), provides insights and analyses on the build environment, sustainability, mobility and safety. Figure 10 provides an impression of what the DIGITWIN can look like. As with the 3DBAG, 3D building information is based on vertically extracting a building's footprint based on height data.

Figure 10 – Impression of Argaleo DT environment (Source: Argaleo, 2021)

Future Insight

Much like Argaleo, Future Insight also provides several services and products within the field of 3D, GIS, BIM and information management. Based on open standards and working from a central database, they provide support and services in development of digital twins for both companies and governments (Future Insight, 2021). As is stressed by Klooster (2020), building a digital twin based on open standards enables a scalable and flexible 3D ecosystem that can be used repeatedly.

Their online viewer called 'Nederland in 3D' provides some insights in how their basic digital twin is build up. Within the viewer, one can choose from several datasets regarding the background, being the BRT, aerial photography or an Openstreetmap layer. Although unable to query those background layers, they do provide visual information. Considering the open data within the viewer, one can choose from 3D BAG Buildings, cadastral maps, municipality boarders or data on land assignment. This data, however, can be queried to provide information on the object of interest.

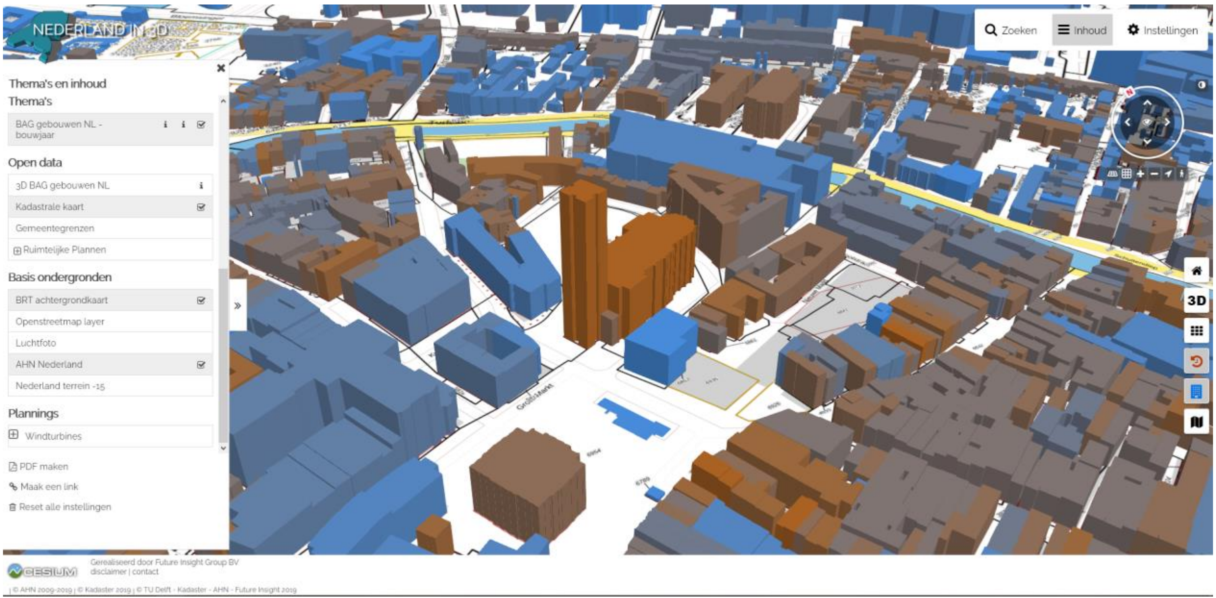


Figure 11 – Impression of 'Nederland in 3D' by Future Insight (Source: Future Insight, https://www.nederlandin3d.nl/viewer/)

City specific projects

More tangible projects regarding 3D city models and digital twins can be seen in several Dutch cities, such as Amsterdam, Rotterdam, and Groningen.

Within the context of the 'Livable Smart Cities by Design' conference, Geodan, Johan Cruijff Arena and the municipality of Amsterdam developed a digital twin for the city of Amsterdam, following from existing smart city projects (BIGnieuws, 2018; Geodan, 2018). Interesting is the approach in which the digital twin, named EcoCraft, is developed as it is built within the game-environment of Minecraft. The way in which this digital twin is presented is based on the target audience, which are citizens for participatory projects and scholars for educational purposes. They hereby putting the focus on usability of the digital twin. Impressions of the resulting DT environment can be seen in Figure 12, showing the 3D model provides a simplified, yet recognisable representation of the real world.

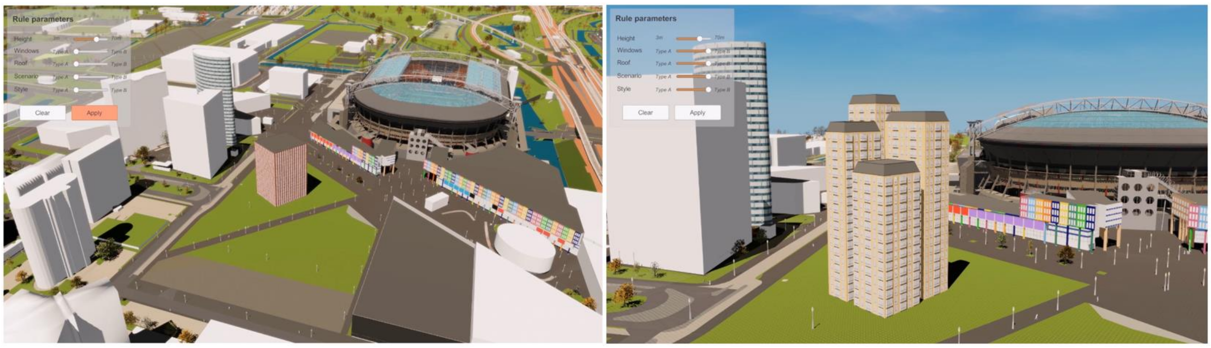


Figure 12 – Impressions of the Ecocraft DT (Source: BIGnieuws, 2018)

Although more system oriented than city oriented, Schiphol airport also created a digital asset twin to manage, monitor and simulate all sorts of processes within the airport (Baumann, 2019). Within the digital twin, featuring more than 80.000 assets, several data sources are incorporated, including BIM and GIS data as well as data on project changes and incidents and real-time sensor data.

ArcGIS's Data Interoperability tool is used to process the BIM data, after which the Schiphol Urban 3D model can be viewed as a web scene. Figure 13 provides an impression of what the digital twin looks like.

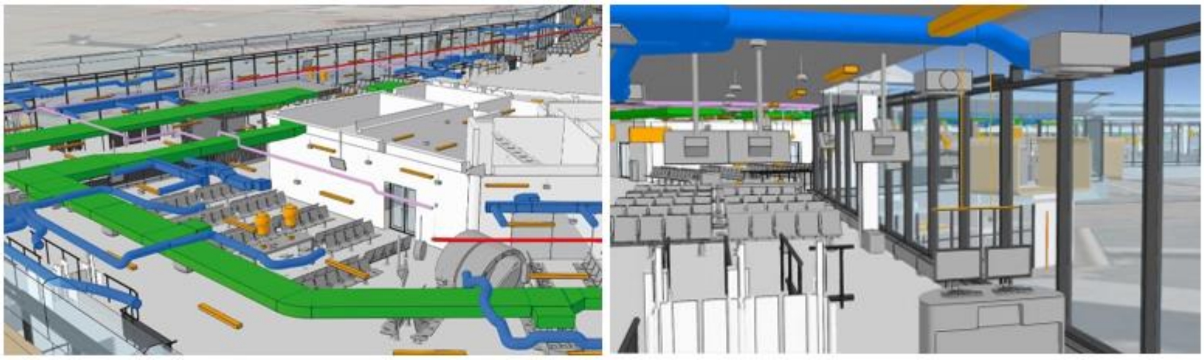


Figure 13 – Impressions of the BIM model for the Schiphol Airport DT (Source: Baumann, 2019)

Concerning the city of Rotterdam, a digital twin is created in order to improve the efficiency of urban planning and management (Coumans, 2019). The digital twin is based on the Kadaster's BAG and BGT data, whereas the 3D buildings are based on AHN point cloud data and textures obtained from oblique aerial photos. This has resulted in a 3D model that represents reality in quite a detailed way as seen in Figure 14.

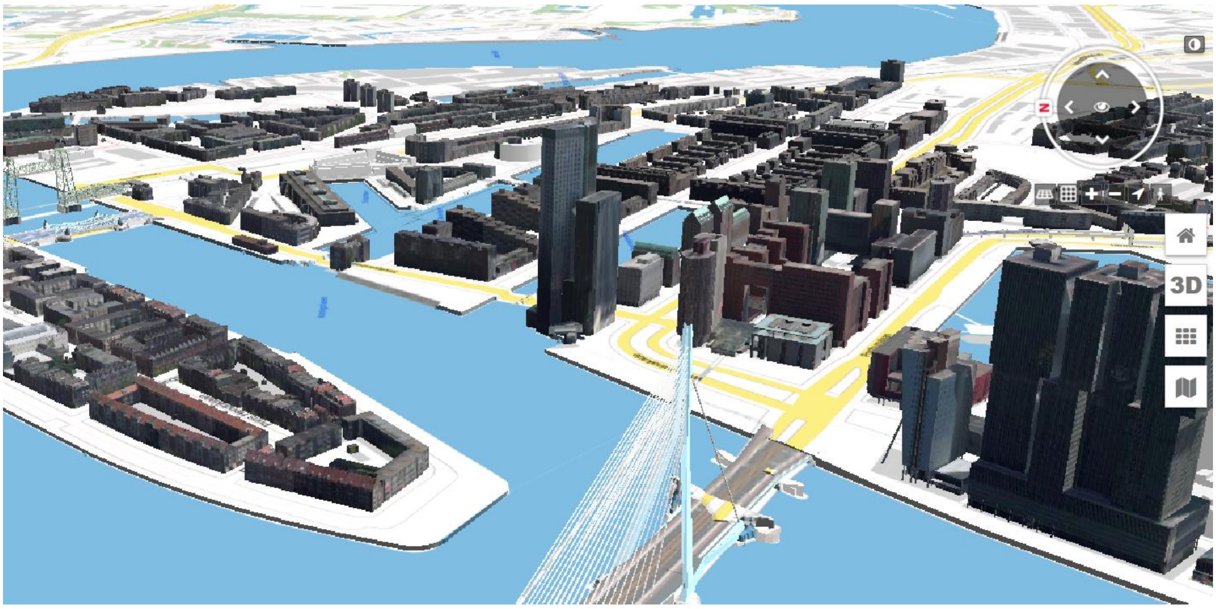


Figure 14 – Screenshot from the Rotterdam 3D city model (Source: 3DRotterdam, https://www.3drotterdam.nl/)

In line with these developments, the city of Groningen has also presented plans to develop a digital 3D model of the city (Gemeente Groningen, 2020), referring to it as the 3D Digital City, in which they explicitly mention the aim to create a digital twin city. Although the development process is in an early stage, the intended build-up of the digital twin is clear as can be seen in Figure 15: The basis of the digital twin is formed by a point cloud for the 3D data, while information and data considering real world objects are obtained from the key registrations provided by the Dutch government, being the BAG, BGT and BRO.

Scope	• Gemeente Groningen

Basis	• Puntenwolk
	• Digitaal Terrein Model (ook BGT)
	  ○ Infrastructuur
	  ○ Openbare ruimte
	• Gebouwen (BAG geometrie)
	• Ondergrond (ook BRO)

Wie	• Opbouw 3D basisbestand extern • Hosting viewer extern • Functioneel beheer intern Geo&Data
Datastandaarden	• Standaard datakoppelingen (CB-NL, NLCS, IMGEO) • Standaard bestandsformaten (CityGML, CAD en BIM)
Nauwkeurigheid **Zie ook toelichting**	• Binnen de diepenring: 1 cm nauwkeurig (> wettelijk BGT niveau) • Buiten de diepenring: 3 dm nauwkeurig (wettelijk BGT niveau) • Nauwkeurigheid projectmatig opvoeren
Detailleringsniveau **Zie ook toelichting**	• Binnen de diepenring: LOD2.3 • Buiten de diepenring: LOD2.0 • Detailleringsniveau projectmatig opvoeren
Beheerafspraken	• Projectmatige bijhouding in het gemeentelijke proces • Tweejaarlijks mutatiedetectie op basis van puntenwolk

Figure 15 – Base layout of the Groningen 3D Digital City (Source: Gemeente Groningen, 2020)

Hereby the point cloud is collected through aerial laser scanning and aerial photography. Within this project, several pilot projects have been rolled out. One of which is the '3D Bovengrond Ten Post'. Figure 16 shows impressions of the 3D model, which is based on a point cloud obtained from aerial photography.

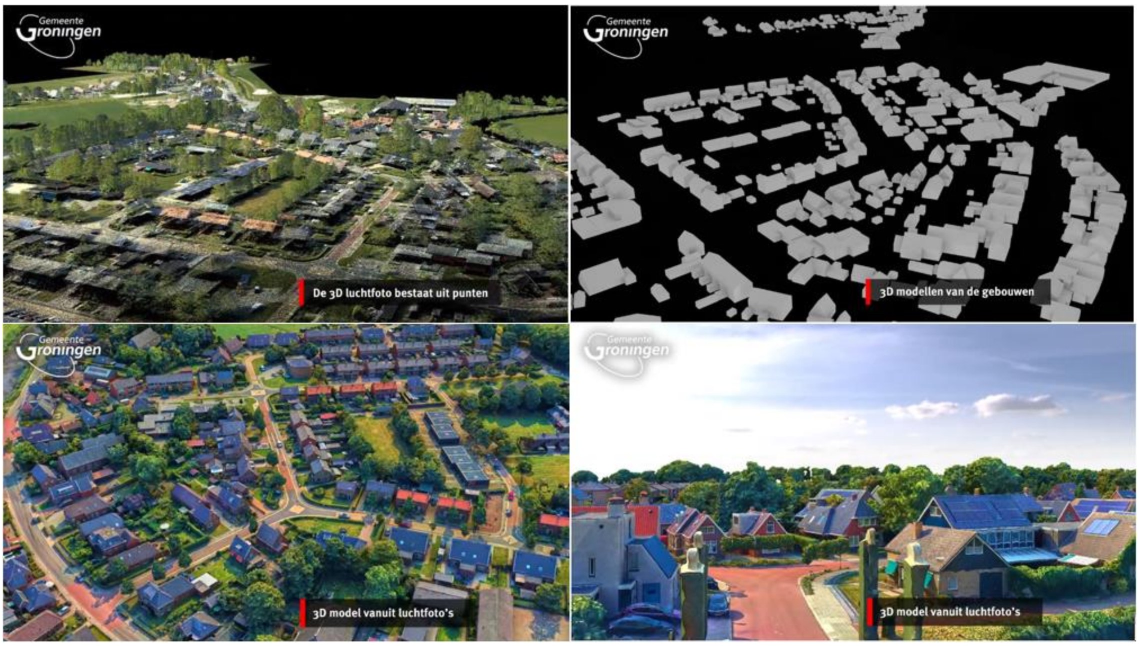


Figure 16 – Impressions of the 3D model based on aerial photos (Source: Gemeente Groningen, 2020)

Industry specific initiatives

There are various industries in which digital twin concept is considered of added value, especially within the context of ongoing digitalization. While some industries, such as the construction industry (Strukton, 2019; Anteagroup, 2019), might be more willing to embrace digital twin technologies, less obvious industries such as the telecom industry (KPN, 2020) also express interest in digital twins. Furthermore, utility companies are increasingly embracing digital twins as well, such as Alliander (2019).

An industry in which digital twins are evidently used is the railway industry, as the use of digital twins is gaining popularity. Several companies address the opportunities of using digital twin within several processes related to railways. Royal Haskoning DHV (2019) addresses the use of digital twin in the design and execution of projects in which integral asset management is a central topic. They also use digital twins in maintenance and operation, in which combining sensor data and IoT technologies is essential. Also Strukton (2020) addresses the added value of digital twins to manage and monitor different aspects related to railway processes, thereby being able to gain insights in the status of the complete rail industry and its data streams.

The government task organisation for railway maintenance ProRail also embraced the use of digital twin, presenting it as their 5D world (ProRail, 2021). The framework of what this should look like is presented in Figure 17.

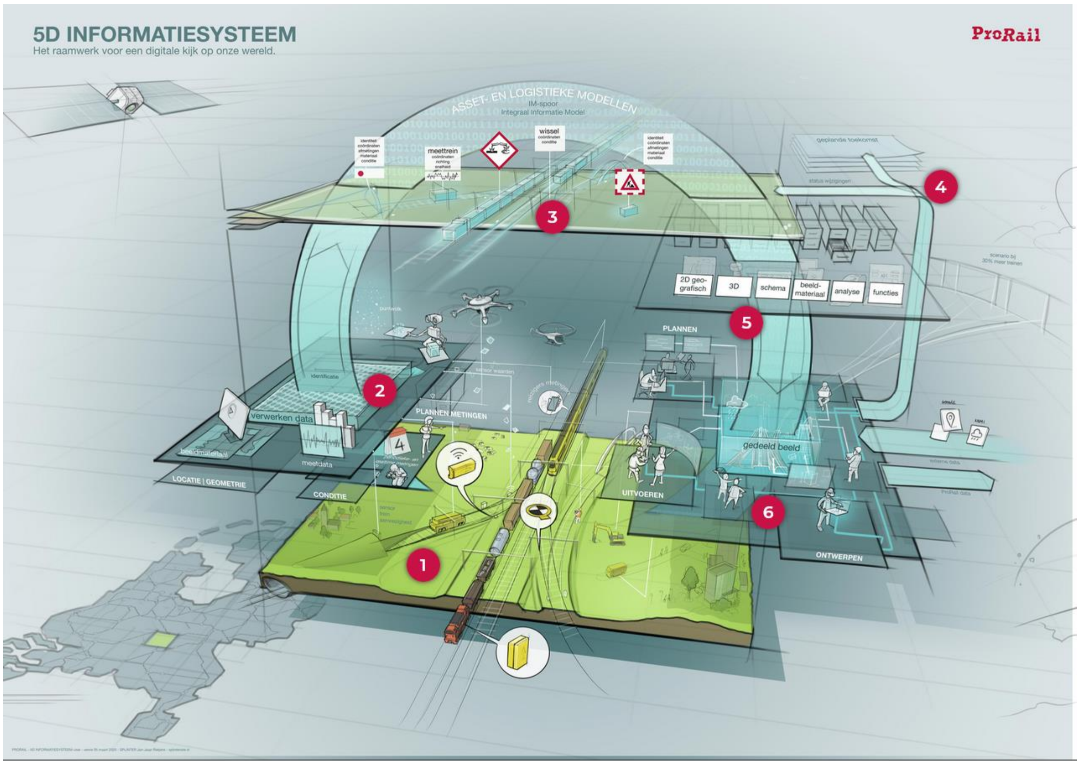


Figure 17 – Framework of ProRail's vision on digital twins (Source: ProRail)

As they describe, the 5D digital twin can be defined as a 3D location based model enriched with a time component and a certain granularity or LoD. Hereby, they stress the importance of the digital twin being able to present both planned or designed objects, as well as disappeared objects. The data used as input for their digital twin is based on streaming data, explaining it as all information gathered by measuring devices being directly sent to a central storage although they also state the current situation requires separate storage of collected data as well, before being extracted.

2. Related work

Within this chapter work related to 3D modelling for digital twins will be discussed. Besides, an overview of projects related to digital twins in the Netherlands will be provided.

2.1 3D modelling

A vast variety of 3D modelling techniques exist, resulting in a variety of 3D depictions in which precision, accuracy and detail differ based on the intended usage. As stated by Yan et al. (2019) construction of 3D models has rapidly developed within the previous decades. 3D models can be derived from a variety of sources, including 2D GIS data, aerial photography, airborne laser scanning and terrestrial laser scanning, to sum up a few. A distinction could be made between the intended usage, being 3D reconstruction methods that focus either on terrain or on the built environment.

For the representation of surfaces, digital elevation models (DEM) are common. In principle, a DEM is a raster map in which the elevation of a surface is generated. This could be done based on several techniques, including LiDAR and photogrammetry. The points captured through these methods are interpolated, resulting in an elevation model. Typical for DEMs is that it represents a bare-earth raster, which means extruding features such as buildings, trees and infrastructure are excluded. This makes DEMs useful in application fields related to hydrology, soil and surface modelling.

Nevertheless, the term DEM is generically used for both digital surface models (DSM) and digital terrain models (DTM). Whereas a DSM represents the earth's surface with both natural and build features (e.g. buildings, infrastructural works, vegetation) on that surface, a DTM only represents the ground surface, similar to a DEM. Unlike a DEM, DTMs also includes the terrain's vector features (e.g. rivers).

Another way of representing the surface is by 3D meshes. As with the generation of raster based DEMs, meshes are generated based on interpolation methods. Meshes can also be generated based on point cloud data. However, unlike raster-based DEMs, meshes are represented by vertices, edges and faces, resulting in sets of polygons. These polygons are generated based on subdivisions in the surface. A common method for generating a mesh model is by triangulation. A triangulated irregular network (TIN) is a vector based data model resulting in a network of non-overlapping triangles. These triangles can be visualized in 3D, thereby also creating a DEM. Although both methods rely on interpolation, the main difference between a raster-DEM and a TIN is that a TIN uses datapoints that can be irregularly divided, thereby allowing for a higher resolution in more variable areas. However, TIN models tend to take more time to process than raster based models due to its complex structure (Esri, 2020).

As Wu et al. (2019) address, mesh models are widely used in 3d representation due to the accurate extraction of geometric information as well as reconstruction of objects in 3D. Since mesh models can be based on point cloud data, combining it with aerial images can result in a detailed representation in which all relevant objects are represented. Nevertheless, meshes are only capable of representing the real world to a limited degree as they interpolate the geometry of a point cloud (Poux, 2020). This becomes evident in Figure 18, showing the process of meshing.

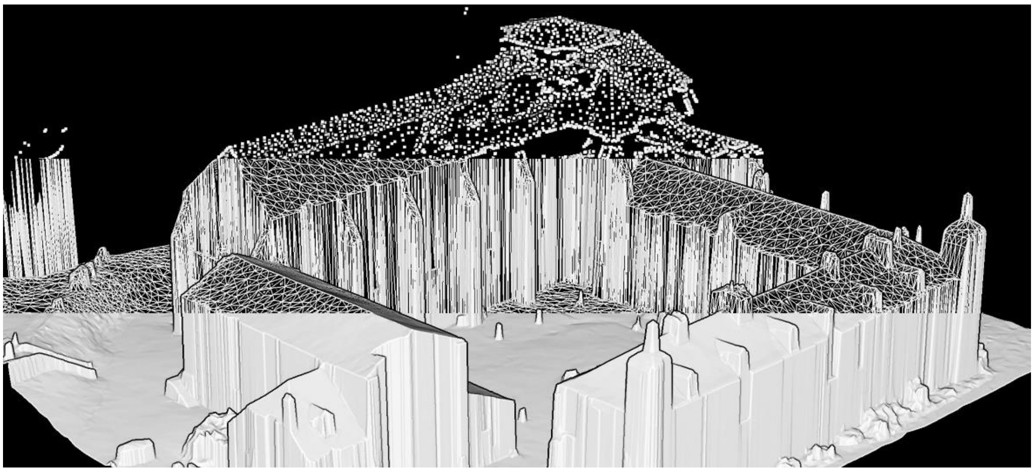


Figure 18 – Meshing process in three steps, top to bottom: Point data as vertices; edges linking the vertices; filled faces based on vertices and edges (Source: Poux, 2020)

For city modelling purposes, trends are moving towards more computer-aided design (CAD) based approaches, considering the complexity of the environment and the amount of detail desired within the 3D model. However, these approaches do not always suffice in providing the desired amount of detail, or even cause certain details to be lost during the modelling process. Especially for representing the build environment in 3D, the Open Geospatial Consortium (OGC) has specified different levels of detail (LoD) in their CityGML open data model, through which a distinction could be made between 3D representations based on the amount of details. It also provides a standard in which 3D representations can be maintained, updated and reused.

As the OGC states, the goal is to provide a shared understanding of the basic entities, attributes and relations of a 3D city model (2012). Within the OGC CityGML standard, various different levels of detail are specified, ranging from. A visual overview of the different LODs can be seen in Figure 19.

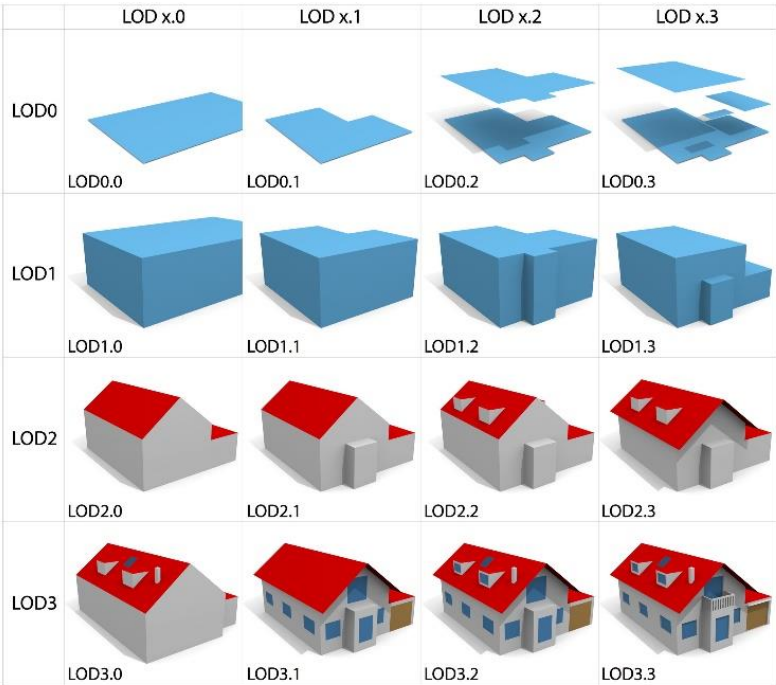


Figure 19 – Levels of detail (Source: Biljecki et al., 2016)

As Biljecki et al. (2016) explain, LoD0 marks the transition from 2D to 3D by representing the footprints of buildings. LoD1 is generally obtained by vertical extrusion of a LoD0 model, resulting in a square block-like object. Roofs are represented in LoD2 models, although simplified, whereas detailed architectural features like doors, windows and balconies can be distinguished in LoD3 models. Further specification of LoDs, being LOD4 and onwards, completes LoD3 models with indoor features.

2.2 3D modelling for Digital Twins

In digital twin development in general, often used methods to derive a 3D model are based on CAD principles, whereas, especially in facility management and construction projects, objects are modelled in 3D apart from each other after which they are integrated. Hereby 3D models are, in some cases, created beforehand, thereby reflecting future objects. In digital twin cities, however, the 3D model is often based on the as-built environment, thereby reflecting the physical structures as they are built, and not as they are designed.

Furthermore, 3D models for digital twin require more than solely providing a visual overview of the subject it reflects. Hereby semantics fulfil an essential role in enabling interpretation of the 3D model by providing thematic and contextual information. Unlike traditional 3D modelling for solely visual purposes, this means that the features within the 3D model need to allow for extra data and information besides the general object characteristics like x, y and z values.

Recent developments and technological advancements have led to an enormous increase in the use of Building Information Modelling (BIM) for the as-built environment, whereas it was predominantly used for design purposes. Nowadays, BIM is a widely used method for generating 3D representations of urban features. Besides, the research field on BIM-GIS integration has been expanding rapidly. Especially in the construction industry, BIM is used to enhance the performance of construction projects from design to actual construction and facilities management (Wang & Kim, 2019).

In general, as Dore & Murphy (2012) state, BIM is used to model new buildings, instead of existing ones. Therefore the need for precise geo-referencing of objects is not essential in the majority of as-designed BIM models. The opposite is true for 3D models used in digital twins, where objects in the 3D model need to correlate with their exact location in the physical world in order to resemble reality as close as possible. Besides CAD based BIM models, however, point cloud data is increasingly being used as input for BIM models as well. The added value herein lies within the accuracy and detail provided by point clouds as well as the storage of geographical location, thereby providing a high quality base for further modelling and design processes.

In general, the usage of point cloud data for 3D modelling has gained enormous popularity, especially due to its high accuracy and detail. However, apart from being used as input, trend are moving towards the direct use of point clouds as the 3D representation itself.

3D point clouds

The research field on point cloud data has been expanding with the growing availability of 3D data, and the commercialisation of LiDAR technologies. At the same time computer power has drastically increased, which makes it possible for computers to process huge amounts of data, such as point clouds consisting of billions of points, more easily, thereby shortening processing and analysis times.

In essence, a point cloud is an unstructured dataset that consist of discrete points in an N-dimensional space, in which a 3D coordinate system represents spatial existence (Richter & Döllner, 2014) and can contain billions or even trillions of points (Liu et al., 2018a). Generally, within this N-dimensional space, each point is defined by at least an X, Y and Z coordinate although additional attribute data can be added to the point cloud data, such as time and colour characteristics (Richter & Döllner, 2014; Wang & Kim, 2019) but also sound, temperature and semantics, like classification (Liu et al., 2018b).

Liu et al. (2018b) further state that these additional attributes can be regarded as extra dimensions, thereby expanding the conventional three dimensions since, conceptually, the terms do not differ. Although their research concerns indoor point clouds, they do address the applicability of point clouds for city models, involving classification information. Furthermore, point clouds allow for selectivity considering wanted and unwanted elements within the 3D representation.

As briefly addressed in paragraph 1.1, there are three main systems for capturing point cloud data, being ALS, MLS and TLS systems. Whereas the choice for usage of either of these systems depends on the extent of the area of interest, the intended usage of the data and the accessibility to aerial or terrestrial vehicles. In their research Pradhan & Sameen (2020) provide a comparison of the performance of these different systems, of which the general results are presented in Figure 20.

ALS	MLS	TLS
Direct view of pavement and building tops	Good view of pavement, unable to capture building tops	Good view of pavement with details
Oblique view of vertical faces	Direct view of vertical faces	Direct view of vertical faces with more flexibility
Fast coverage	Slow coverage	Slower coverage
Large footprint	Small footprint	Small footprint
Far-range travel	Short-range travel	Short-to-moderate range travel
Not limited to the area visible from the roadway	Limited to objects close to and visible from the roadway	Limited to objects close to the roadway
Low point density (1–60 point/m^2)	High point density (100 points/m^2)	Very high point density (500 points/m^2)
Limited options for setup locations	Good options for setup locations	Better options for setup locations
Difficult to operate and requires adequate training	Difficult to operate but easier than ALS as a pilot is not needed	Easy to operate with less training
Provides a low level of details	Provides a high level of details	Provides the highest level of details
Low accuracy and resolution of road features	High accuracy and resolution of road features	Higher accuracy and resolution of road features
Highest cost-effectiveness	High cost-effectiveness	Low cost-effectiveness

Figure 20 – Comparison of ALS, MLS and TLS scanning systems (Source: Pradhan & Sameen, 2020)

In 3D representation, using point cloud data has several advantages over traditional methods. Most of the current popular 3D modelling techniques require multiple processing and analysis steps, as well as manual interference. Although the result may be sufficient for its intended usage, details may still be lacking as the 3D data is often interpolated or simplified, while the development process might be time consuming. These limitations can be overcome by using point cloud data. Benefits lie within the precision, accuracy and density in which the environment is captured and represented. Hereby complex structures as tree branches and foliage can be represented in very high detail, just as building facades with balconies, for example. A major advantage, however, lies within its direct usage.

A growing body of research is dedicated to the possibilities of using the raw point data directly for a variety of purposes, such as indoor mapping (Grasso et al., 2017), visibility analyses (Zhang et al., 2017; Díaz-Vilariño et al., 2018; Zhang et al., 2021) and first-class representations (Van Oosterom et al., 2019). By directly using the point cloud data, processing procedures such as generating surfaces can be skipped, resulting in much shorter analysis periods and reduced costs. Besides, with the combination of high-definition cameras, point clouds are able to reflect the physical world in photorealistic detail, thereby allowing for a truthful experience in using point clouds directly as 3D geometric model for a digital twin, as it perfectly represents the built environment as-is.

An example of these techniques put into practice can be seen in the city of Amsterdam, where the company Leap3D works on generating point cloud data of all bridges in Amsterdam in order to map the current states of these bridges. Thorough on-sight observations are linked directly to the exact location within the point cloud, while additionally the point cloud is linked to archive data. Although the resulting product represents the real world at a certain point in time, it can be considered a digital twin given the point cloud is used as the 3D model itself while additional data and information is directly linked. Merely updating the data and information provides a working, point cloud based digital twin. Impressions of the point cloud of the Drieharingenbrug can be seen in Figure 21.

Figure 21 – Point cloud of the Drieharingenbrug (Source: Leap3D, 2019)

Another example in which point clouds are used in practice to provide insights in the current state of real world objects can be seen in Rotterdam, where the company Geomaat generated a point cloud of the ‘Van Brienenoordbrug’. By combining laser scanning and 360 photography, a detailed 3D point cloud of the bridge has been obtained. However, unlike the case in Amsterdam, the point cloud serves as input to derive a DTM, thereby involving extra processing steps in order to create the resulting product of which an impression can be seen in Figure 22. In order to serve as a functional digital twin, interaction between the point cloud and DTM is essential in the sense that changes to the point cloud will result in corresponding changes to the DTM in the case of change to the physical object.

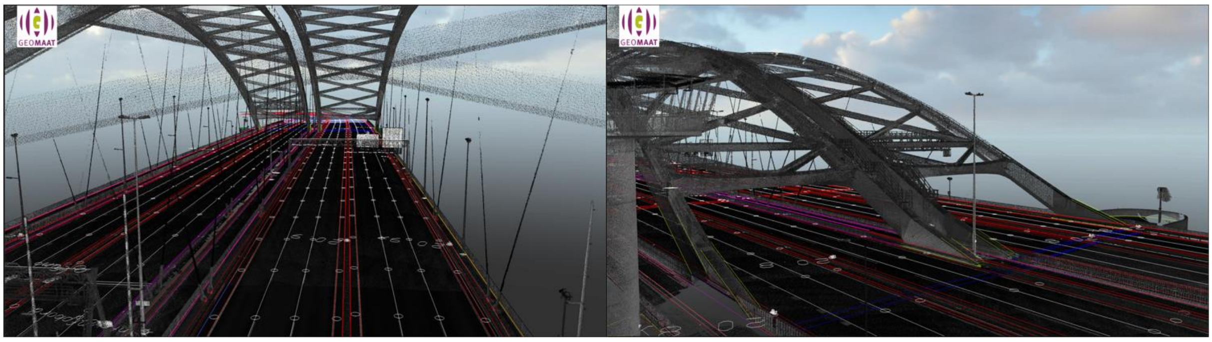


Figure 22 – Van Brienenoordbrug point cloud & DTM representation (Source: Geomaat, 2020).

These examples show the added value of directly using point cloud data to act as the 3D geometric model. Moreover, it shows that directly using the point cloud still allows for the functionalities desired in a digital twin, being to examine and monitor physical objects and processes digitally, thereby enriching the 3D model with external information the same way in which general digital twins are used.

Smart point clouds

One of the main features of a digital twin is to be able to interact with the 3D data, being positional e.g. orientation and navigation as well as informational e.g. querying and computation. Positional data (e.g. GPS) and visual information (e.g. aerial photos) are often already combined with or integrated within the point cloud data thereby allowing for navigation through and positioning within the point cloud.

Besides, the point cloud initially allows for basic computation and analysis on the geometry. However, in order to perform object specific or thematic analyses, additional information needs to be integrated within or linked to the point cloud, such as topology or sensory data. The process of a point cloud becoming ´smart´ is often referred to as enrichment or semantic enrichment (Poux et al, 2016). In principle, as briefly addressed, a point cloud is a collection of unstructured points. However, every point represents part of an object whereas groups of points represent complete objects and features. In order to enrich the point cloud with the knowledge that certain points represent a certain feature, popular methods involve segmentation and classification.

Segmentation is the process of classifying points into homogenous regions, meaning points within the same region are considered to share the same properties (Nguyen & Le, 2013). Hereby the point cloud is provided the knowledge that certain points belong to the same object. This is useful since it enhances the possibilities of analyses regarding object recognition, classification and feature extraction. Moreover, Nguyen and Le (2013) address several methods for point cloud segmentation, whereas they stress that the algorithm for doing so should at least be able to distinguish different feature properties (e.g. trees vs. cars). Furthermore, the algorithm should be able to automatically trade of different features, while also being able to adapt to different laser scanners. The discussed methods are presented in Figure 23.

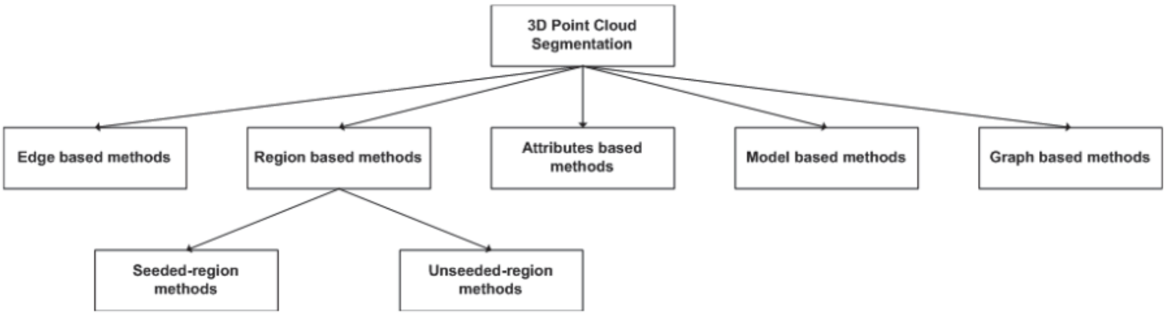


Figure 23 – Overview of existing point cloud segmentation methods (Source: Nguyen & Le, 2013)

The different methods are based on different aspects within the point cloud. Whereas edge based methods and region based methods respectively take into account the shape of features or neighbourhood information, attribute based methods calculate attributes after which points will be clustered based on those attributes. Model based methods rely on geometric shapes to group points. A well-known algorithm for model based methods is the Random Sampling Consensus (RANSAC). Lastly, graph based methods approach the point cloud as a graph. As they state, in a simple graph based segmented model, vertices correspond to points in the data while edges connect these points to pairs of neighbouring points.

Semantic segmentation of a point cloud is considered essential in understanding a 3D scene, as stated by Han et al. (2021). Especially in recent years, a growing body of research is dedicated to the application of deep learning and machine learning techniques. Also so for point cloud segmentation and semantic enrichment.

A logical step after segmentation is classification. As segmentation already classifies points based on shared characteristics, the resulting segmented point cloud provides information of all individual features. Hereby, for example, every tree is considered as a separate class. Using classification methods, features with sharing characteristics will be divided into classes describing these characteristics, such as vegetation, buildings or cars.

More advanced research within the domain of smart point clouds is done by Poux (2019). In his research he proposes an intelligent infrastructure for point clouds in which users can extract specific information based on semantic memory. Hereby, he also underlines the importance of segmentation and classification as essential in providing this added value. A visual example of how a semantic point cloud representation can look like is shown in Figure 24.

Figure 24 – 3D point cloud representation (left) and a 3D semantic representation (right) (Source: Poux, 2019)

Point cloud visualization

As with 2D maps, considerations on the visualization of 3D data are important. Especially for communication purposes as well as the understanding and interpretation of the data, visualization and presentation techniques are essential (Kreylos et al, 2008, Bettio et al., 2009, Kim & Medioni, 2010). Point cloud visualization, as addressed by Azari et al. (2012), has recently become a topic of interest in a variety of application fields. The relevance of applying visualization methods and techniques on point cloud data is addressed by Verbree & Van Oosterom (2015), saying these methods and techniques aid the end-user in gaining insight and understanding of the objects represented by the point cloud data. Hereby, interactive and explorative visualization techniques are of great importance.

Poux (2020) describes the most common ways of visualizing point clouds data. The first visualization is direct representation, which shows the point cloud as is. Although the quality and completeness of the data depends on the capturing method, it provides an exact representation. Figure 25 shows direct representations of point clouds acquired through photogrammetry (left) and LiDAR (right).

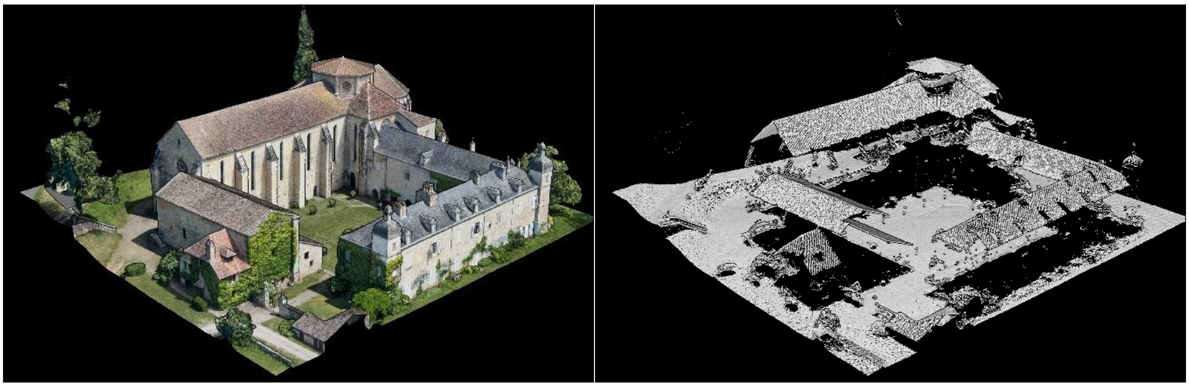


Figure 25 – Direct point cloud representations (left: Photogrammetry, right: LiDAR) (Source: Poux, 2020)

Other visualization methods commonly rely on surface reconstruction. Hereby, a distinction can be made between solid representations and shell or boundary representations. Whereas shell representations only represent and objects´ surface, solid representations also define the volume of objects. A common method for shell representations is meshing, as is addressed in paragraph 2.1. For solid representations, a common used method is based on voxels. Voxels can be seen as ´3D pixels´, whereby each point is represented by a voxel with a certain size in order to provide volumetric information.

2.3 Change detection

As urban environments have always been changing over time, detection of change in remote sensing is not a new topic of research, resulting in the development of various change detection methods and techniques. Traditionally, change detection has been performed on 2D images by analyses comparing spectral values within the images (Lu et al., 2014) although 3D change detection has recently been introduced to the research field.

2D change detection

In general, 2D based change detection methods offer the benefits of being well investigated, while data is easily collected and the methods are easily implemented as stated by Qin et al. (2016). Though, a distinction could be made between methods for aerial and terrestrial images.

First of all, aerial images have the limitation of solely providing a top down view of the area of interest (Qin and Gruen ,2014). Although the height and angle of the capturing device might influence the visibility of objects within the image, facades of buildings are almost always invisible while on the other hand views can be blocked by foliage of trees. Nevertheless, 2D aerial image change detection methods have proven to be successful in detecting changes for environmental purposes such as forestry and flood risks (Ilsever & Ünsalan, 2012; Qin et al., 2016). Hereby, two methods can be generally distinguished as described by Hussain et al. (2015), being pixel based and object based methods. Whereas pixel based methods focus merely on analysis of the pixel values within the images, object based methods also incorporate textures, shapes, and relations to surrounding objects, thereby including spatial context.

For detecting change in urban environments, however, aerial images have shown to be useful as well. Hou et al. (2016), for example, propose a method for detecting changes on buildings through aerial images by combining both object and pixel based methods. Terrestrial images overcome the limitations of aerial images when it comes to building facades and blockage by trees.

However, drawbacks lie in the time and effort needed to invest in capturing a whole city, although this process has been enhanced by technological developments and the emergence of omnidirectional cameras that can be easily mounted on vehicles. A method proposed by Sakurada et al. (2013) that uses the technology described previously, compares two panoramic images of the same area but from different points in time. This approach has also been adopted by Taneja et al. (2013), as they make use of images from Google Street View. The difference, however, lies in the comparison. Whereas Sakurada et al. (2013) compare images of the same area to each other, Taneja et al. (2013) compare the freely available images to an existing 3D point cloud of the same area.

Although using images from Google Street View may seem a low effort but efficient method, there are some limitations as Qin & Gruen (2014) and Kang & Lu (2011) explain. Weather conditions can influence lighting and shadows within the images, whereas the perspective can cause distortion. Also unwanted elements such as street furniture and other vehicles might be present and block the view. Moreover, the recency of the images depends on the update frequency, which is known to be variating, even within the same area.

3D change detection

The topic of 3D change detection, as mentioned by Qin et al. (2016), is relatively new and mostly driven by the increasing access to 3D data as well as its usage in smart cities. The extra dimensional information compared to 2D images provides more functionalities for change detection in terms of viewing perspective as well as level of detail. Limitations of 2D change detection are overcome as 3D data reflects the physical geometry of real-world objects, thereby allowing for much precise analyses. The input 3D model for performing change detection can be in several forms, ranging from stereo images to Digital Elevation Models (DEM) and point clouds. As Qin et al. (2016) point out, the quality of the 3D model dictates the quality of the change detection result. Thereby accuracy, completeness and resolution are the main characteristics. LiDAR point cloud data has proven to be a reliable data source when performing 3D change detection, especially considering the increasing access to low-cost and lightweight LiDAR scanners for both aerial and terrestrial systems.

For detecting change in urban environments, terrestrial and mobile scanning systems are preferred. As Qin et al. (2016) state, LiDAR has great advantages in terrestrial and close-range scanning considering it offers high quality geometric information of complex environments. Something in which images fail to perform good at. Combined with the growing availability of and accessibility to LiDAR scanners that can be mounted on all sorts of vehicles, this means areas of interest can be easily captured in high quality with relatively low costs and effort.

Methods for performing 3D change detection on MLS point clouds have been researched and developed. Qin et al. (2014) for example propose a method in which terrestrial images are compared to an MLS point cloud. Hereby geometric consistency is compared. In order to do so, however, the point cloud and the images have to be co-registered, a process that can be done manually or automatically. Whereas several automatic co-registration approaches have been developed that take into account RGB values, homogenous areas do not perform good. To resolve this, Mobile Mapping Systems (MMS) can be of added value, considering the captured images are assigned geo-tags that are linked to the reference point cloud. However, the limitations of using images in complex environments are known.

Another method, however, is proposed by Xiao et al. (2015) which compare new LiDAR scans to an existing point cloud, thereby considering the occupancy of space. Within this analysis, points are assigned local cylindrical reference frames that measure consistency in occupancy. When the consistency in space occupancy differs between the new LiDAR scan and the existing reference point cloud, thereby being conflicting, this means change is detected. However, when performing close-range scans, which is the case in most urban environments using MLS, caution is needed as oblique views and occlusion might result in false positives for change detection (Qin et al. 2016).

Eventually, the aim of performing change detection is to update the existing point cloud functioning as 3D model for a digital twin. Since change occurs at different times at different areas within a city, questions arise concerning re-scanning of the city. To make the process of detecting change and updating the 3D model as efficient as possible, Richter and Döllner (2014), among others, propose selective updating of the 3D model. Major advantages of this approach involve cost and time reduction, while also efficiency in storage is achieved. This means unchanged areas do not have to be re-scanned. Nevertheless, choices need to be made between automation and manual interference. A research field that has gained an increasing amount of interest recently is in automating the processes of object recognition in, and attributing semantics to the 3D point cloud through classification (Velizhev et al., 2012; Hu et al., 2013; Che et al., 2019). These developments are strongly enhanced by technological advancements regarding deep learning and machine learning (Luo et al., 2019).

2.5 Temporality

Within geospatial modelling, the concept of time is regarded as an important dimension (James et al., 2012). Whereas traditionally three dimensions were defined being the x, y (2D) and z (3D) dimensions, time can be considered as the fourth dimension and is increasingly being regarded as such. As changes in the physical environment occur, the main focus is on the *what* and *where*. However, *when* a change happened is just as important.

In general, a digital twin represents the state of the real world at a certain point in time. Its actuality is defined by the validity and recency of the data it is composed of. In terms of the geometric model, this means the objects represented in the digital twin inherently represent that point in time. However, as James at al. (2012) address, historical representations can be of great added value. Digital twins can have a key role in doing so by approaching it not only as an actual representation but also as an historical archive. The relevance for doing so can be seen in application fields ranging from geomorphology, to Architecture, Engineering and Construction (AEC), in which the availability of and access to historical data aids the monitoring process.

Considering the concept of time in GIS, some temporal basic principles can be distinguished (van Oosterom, 2010). Within spatio-temporal modelling, the concept of a timeline is widely used. This implicates that time has a certain direction in which it is constantly moving. Hereby, the point defined by 'now' is special as it is constantly moving rightwards, while keeping the boundary between the past and the future. However, although an object in the digital twin represents the 'now', it can be argued it also represents the past. This means that objects should at least be provided with a time interval indicating its validity. Furthermore, a distinction can be made between so-called 'world time', being the time at which an object exists in the real world and the 'system time', which is time at which that object exists in a database.

3. Methodology

3.1 Research design

This chapter provides an overview of the methods to be used in this research in order to meet the research objectives and provide answers on the research questions.

In order to provide an answer on the main question, sub-questions supporting the main question require answering first. To do so, the approach will consist of multiple methods that can be divided in a theoretical and a practical approach.

Answering the first sub-question 'To what extent can point clouds be used directly to represent a high quality digital twin?' will be done by executing a theoretical exploration, supported by a practical execution in which a point cloud based city model will be used to represent a digital twin. First the necessary data will be collected and requirements regarding the data need to be established as well as requirements regarding suitable software. Part of the objective is to present a digital twin that is represented by a point cloud. Considering that the focus of this research is on the Dutch context, data provided by the Dutch government (e.g. AHN, BAG, BGT) will be the most promising to look into. Steps needed to present a digital twin will be based on thorough theoretical research. The intended result will be a starting point for a functional, high quality digital twin.

The second sub-question 'To what extent can point cloud data be used for change detection in a physical environment?' will also be answered through a theoretical exploration regarding the subject, and will result in an overview of existing methods as well as an advice regarding the most suitable one given the context, circumstances and objectives within this research. Besides, the aim is to present the digital twin in such a way that change detection methods will be applicable in respect to updating the geometrical model of the digital twin.

Sub-question three, being 'What are the practical implications regarding change detection and frequencies for updating the digital twin?' will elaborate on the second sub-question, in terms of managing the acquired data. This question will be answered based on related work and the practical exploration of point cloud data representing a digital twin. Furthermore, a strategy will be proposed regarding the most desirable frequency in terms of change detection and updating the geometric model. These insights will follow from existing work and current applications of relevant technologies.

Eventually, having answered all three sub-questions, the main question can be answered by combining insights gathered through both the theoretical study and the practical exploration in which point cloud data is used to represent a digital twin. However, whereas the objective initially is to present a point cloud as a prototype digital twin, this will not be a final goal. The practical exploration is merely meant to apply and support the theoretical basis, and to support the concept laid out in this research. The overall workflow of this research is depicted in Figure 26.

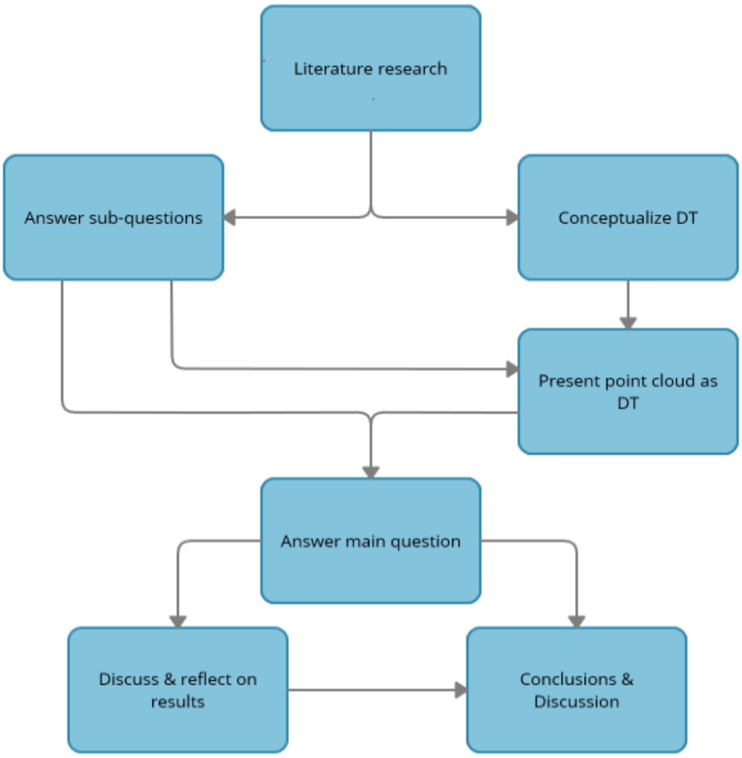


Figure 26 – Research workflow (Source: Own work)

Literature research

In order to provide theoretic insights and understanding of the concepts and topics related to this research, a literature study has been carried out as presented in chapter 2. Herein, related work on several topics has been discussed, being 3D modelling techniques, 3D modelling for digital twins, the principles and applications of point cloud data and change detection principles.

Scientific as well as non-scientific resources have been consulted for relevant studies and articles. These have been accessed through the broad range of catalogues and research deposits available online and through the Universities of Utrecht and Delft, as well as Google Scholar and other online repositories, whether or not accessible via institutional login.

Conceptualize digital twin

The aim of this research is to explore the extent in which a point cloud is able to directly represent a digital twin. In order to do so, the basic requirements of a digital twin will need to be determined. Literature as well as current initiatives regarding digital twins will be consulted to formulate these requirements, which can be applied to a point cloud representation.

The first step consisted of a deduction of the main features of a digital twin, as described in scientific literature. These concepts and characteristics have been used to assess whether a point cloud fulfils these requirements. The next step has been an exploration of existing digital twin initiatives in the Netherlands. By describing the way in which these digital twins and 3D city models represent reality, a basic understanding of the general characteristics has been obtained. The third step was to find corresponding characteristics and features that form the basic requirements of a digital twin city.

Present point cloud as digital twin

It is not in this research's interest to develop a fully functional, high-end digital twin, nor is it to reinvent existing solutions. As there already is a huge amount of different forms of 3D models, digital twins, 3D point cloud visualizations and other digital representations of reality in existence, it is deemed not of added value to develop such a representation from scratch.

Besides, different representation techniques are extensively addressed and described in available scientific and business specific literature. Therefore, it is deemed of more interest to provide insights in the existent techniques rather than exploring new ones.

Furthermore, it is evident there is no right way of representing reality in a digital or virtual counterpart. Based on the context in which a 3D representation is created, the requirements and functionalities differ enormously.

In line with these thoughts, the aim is to provide insights in the direct use of a point cloud as a digital twin representation by showing its capabilities of directly representing the real world, not by developing a point cloud based digital twin. As various point cloud datasets are freely available and software for rendering, viewing and perform measurements and analyses on point clouds is also accessible, this research will use these to present a proof of concept. This means performing measurements and analyses on point cloud data does not fit the objectives of this research, which in essence will be a theoretic, hypothetic approach strengthened by the accessible possibilities regarding data and software for presenting point cloud data.

3.2 Point cloud data

In order to present a point cloud as digital twin, appropriate data is needed. The data can be selected by first determining the basic requirements. The main criterium is that the point cloud should at least provide recognizable shapes (e.g. buildings), as acquisition methods affect the completeness as well as accuracy of the point cloud. This leads to the second requirement, being the availability of both arial as well as terrestrial obtained point clouds. Furthermore, the availability of data of the same area, captured at different points in time is essential to detect changes. Furthermore, as it is deemed important for the point cloud to be a realistic representation, it is required that the points are RGB coloured. Based on these requirements, the following datasets are considered to be useful in this research.

AHN

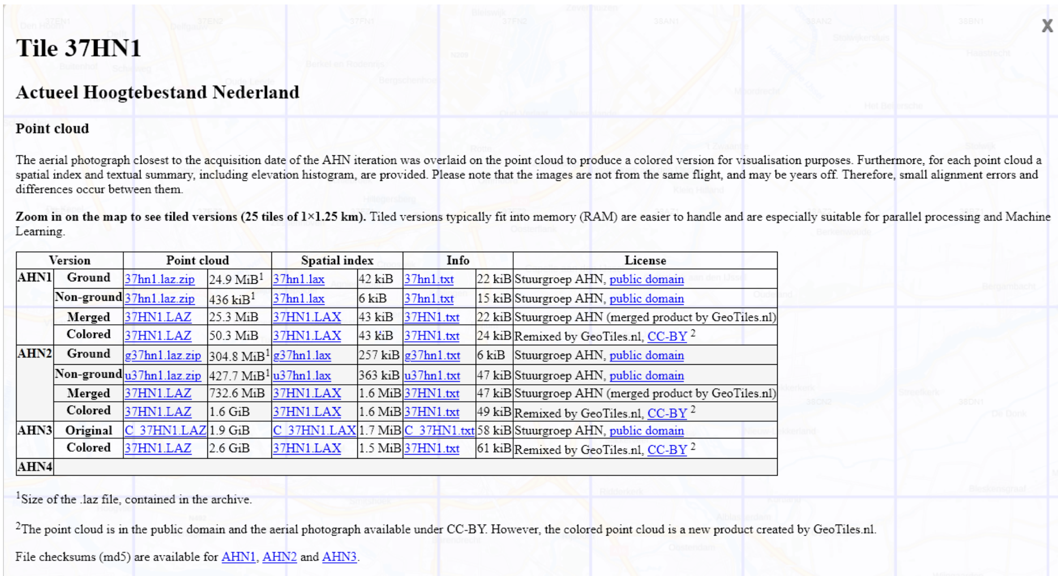
The Dutch governments facilitates a variety of open data, of which the national height model is widely used. The 'Actueel Hoogtebestand Nederland' (AHN) is a point cloud dataset acquired through laser altimetry and covers height information of the Netherlands in the form of raster DSM, raster DTM and point cloud (.LAZ). For this research, the point cloud dataset will be of main interest. The complete download extent of the AHN datasets, however, can be over 1 terabyte in size. In order to facilitate easier downloading and handling of the data, the complete extent of the dataset is divided into separate tiles, representing an area of 6.25 km by 5 km resulting in approximately 1100, individually numbered data files (AHN, 2014). Although the different AHN datasets are distributed through the Dutch government's open data portal PDOK, one can also access the data via the Esri ArcGIS online environment or Geotiles.com. The latter also provides access to additional datasets, such as aerial photographs, when selecting a tile of interest. Furthermore, a coloured version of the AHN3 dataset can be downloaded.

At the moment, there are three complete versions of the AHN available for viewing and downloading, of which AHN3 is the most recent version. However, the developments for AHN4 are in operation, of which concept point clouds of two tiles have been made available: tile 25GN1 (Amsterdam) and 31HZ2 (Utrecht).

The point density of the AHN datasets varies per dataset as well as per area within the a individual dataset. As is stated by AHN (2020), the point density of AHN1 ranges from 1 point per 16m^2 to 1 point per m^2. For AHN2 and AHN3 the average point density is estimated to lie between 6 and 10 points per m^2, although no precise point density is specified. Considering AHN4, the average point density is estimated to range from 10 to 14 points per m^2.

As this research does not particularly focuses on a specific region in the Netherlands, areas of interest have been chosen based on well-known locations, the presence of iconic buildings and personal preference.

Using geotiles.nl, a tile that encompasses an area of interest can be easily selected after which the preferred data can be downloaded. Figure 27 provides an overview of the available AHN data for tile 37HN1 (Rotterdam). As can be seen one can easily download the different AHN datasets of the area of interest. Moreover, it offers all datasets as coloured point clouds if desired.


X

Tile 37HN1

Actueel Hoogtebestand Nederland

Point cloud

The aerial photograph closest to the acquisition date of the AHN iteration was overlaid on the point cloud to produce a colored version for visualisation purposes. Furthermore, for each point cloud a spatial index and textual summary, including elevation histogram, are provided. Please note that the images are not from the same flight, and may be years off. Therefore, small alignment errors and differences occur between them.

Zoom in on the map to see tiled versions (25 tiles of 1×1.25 km). Tiled versions typically fit into memory (RAM) are easier to handle and are especially suitable for parallel processing and Machine Learning.

Version		Point cloud		Spatial index		Info		License
AHN1	Ground	37hn1.laz.zip	24.9 MiB[1]	37hn1.lax	42 kiB	37hn1.txt	22 kiB	Stuurgroep AHN, public domain
	Non-ground	37hn1.laz.zip	436 kiB[1]	37hn1.lax	6 kiB	37hn1.txt	15 kiB	Stuurgroep AHN, public domain
	Merged	37HN1.LAZ	25.3 MiB	37HN1.LAX	43 kiB	37HN1.txt	22 kiB	Stuurgroep AHN (merged product by GeoTiles.nl)
	Colored	37HN1.LAZ	50.3 MiB	37HN1.LAX	43 kiB	37HN1.txt	24 kiB	Remixed by GeoTiles.nl, CC-BY [2]
AHN2	Ground	g37hn1.laz.zip	304.8 MiB[1]	g37hn1.lax	257 kiB	g37hn1.txt	6 kiB	Stuurgroep AHN, public domain
	Non-ground	u37hn1.laz.zip	427.7 MiB[1]	u37hn1.lax	363 kiB	u37hn1.txt	47 kiB	Stuurgroep AHN, public domain
	Merged	37HN1.LAZ	732.6 MiB	37HN1.LAX	1.6 MiB	37HN1.txt	47 kiB	Stuurgroep AHN (merged product by GeoTiles.nl)
	Colored	37HN1.LAZ	1.6 GiB	37HN1.LAX	1.6 MiB	37HN1.txt	49 kiB	Remixed by GeoTiles.nl, CC-BY [2]
AHN3	Original	C_37HN1.LAZ	1.9 GiB	C_37HN1.LAX	1.7 MiB	C_37HN1.txt	58 kiB	Stuurgroep AHN, public domain
	Colored	37HN1.LAZ	2.6 GiB	37HN1.LAX	1.5 MiB	37HN1.txt	61 kiB	Remixed by GeoTiles.nl, CC-BY [2]
AHN4								

[1]Size of the .laz file, contained in the archive.

[2]The point cloud is in the public domain and the aerial photograph available under CC-BY. However, the colored point cloud is a new product created by GeoTiles.nl.

File checksums (md5) are available for AHN1, AHN2 and AHN3.

Figure 27 – Screenshot of data overview on Geotiles

Furthermore, when zooming further on a tile of interest, the main tiles are divided in smaller tiles. This enables the downloading of even smaller datasets if desirable.

Eindhoven

As part of a project regarding the development of a 3D model, the municipality of Eindhoven and Leap3D provided a point cloud of part of the 'Stratumseind' area in the Eindhoven city centre. The point cloud consists of 257.401.153 points and is obtained by a terrestrial LiDAR scanner. The points have been coloured based on simultaneously capturing HDR 360 photos (Leap3D, 2018).

3.3 Software

In order to be able to view point cloud data and explore its functionalities, suitable software will be needed. Although there are various software packages available for doing so, software specially dedicated to point cloud data is preferred. Whereas professional software like Esri's ArcGIS Pro provides extensive functionalities for both 2D and 3D analyses, limitations lie in loading large point cloud datasets causing the software to drastically slow down or crash. Furthermore, ArcGIS Pro is only available through paid licenses. QGIS, although providing an open source, easy to use environment, only recently integrated point cloud rendering functionalities. However, just like ArcGIS Pro, the software has trouble handling large point cloud files.

Two software packages that are freely available are Potree and CloudCompare. As they are both specifically dedicated to point cloud data, these programmes are preferred for usage in this research.

PotreeDesktop

Potree has originally been developed as a free, open-source WebGL based point cloud renderer in which large point clouds can be viewed and explored. Earlier versions of the Potree environment required hosting a webserver in order to load, render and view point cloud data. However, continuous development has led to a freely downloadable desktop viewer in which point clouds can easily be imported by dragging and dropping. The latest release, being PotreeDesktop 1.8, is available through https://github.com/potree/. The software easy to download and install, after which it can be directly used.

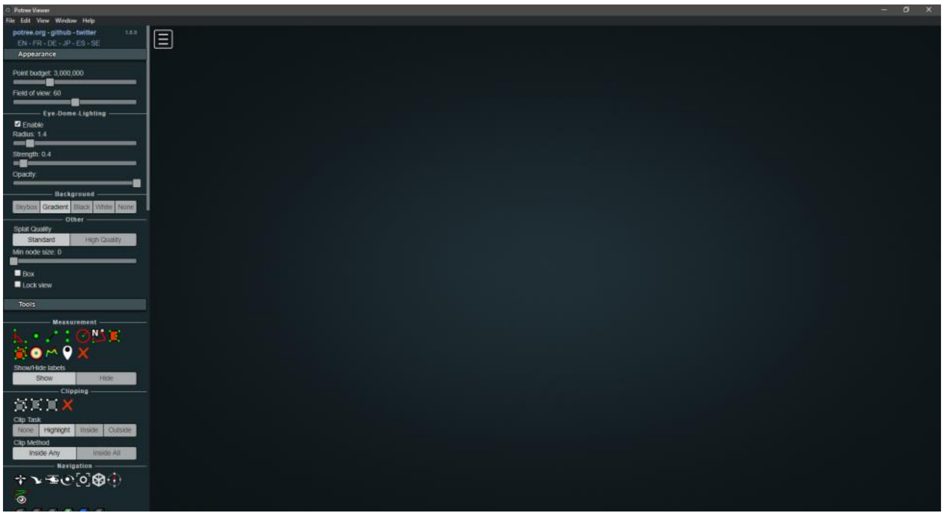


Figure 28 – Screenshot of the empty PotreeDesktop interface

As stated, point cloud data (.LAS/.LAZ) can be loaded by dragging and dropping it into the viewer. Potree then converts the point cloud to generate an octree LoD structure that is stored in a binary format. This process is necessary in order to provide streaming and real-time rendering options for massive point clouds. An example of a point cloud loaded in the viewer can be seen in Figure 29.

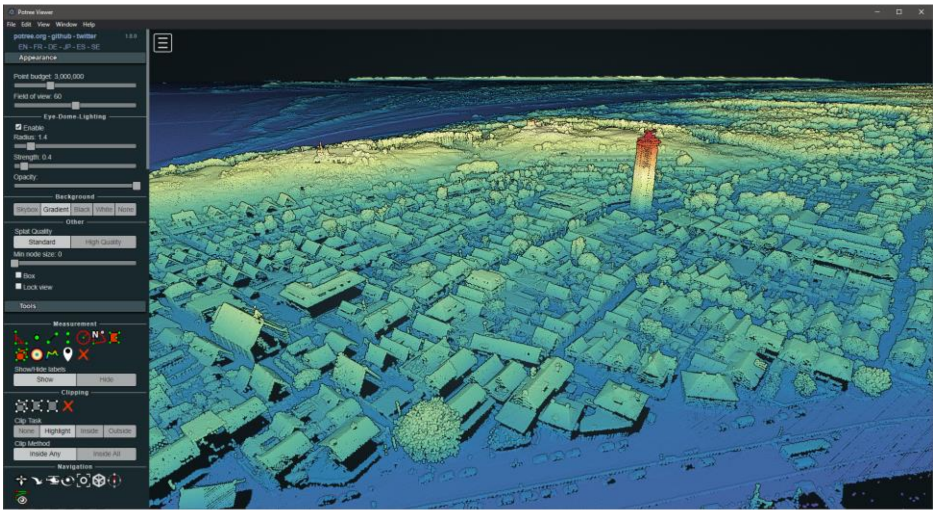


Figure 29 – Point cloud imported into the PotreeDesktop environment (Source: AHN3)

Besides viewing, Potree offers several functionalities for performing basic operations on the point cloud data. Hereby, the viewer facilitates several types of measurement, cropping and clipping tools, while also allowing for the adjustment of several visualization and navigation options.

CloudCompare

Cloudcompare also is an open-source software package that is developed especially for large point clouds and, more specifically, to compare two point clouds. This provides an advantage over PotreeDesktop as multiple point clouds can be loaded and viewed at once. The latest release, being version 2.12 alpha, can be easily downloaded from https://www.danielgm.net/cc/.

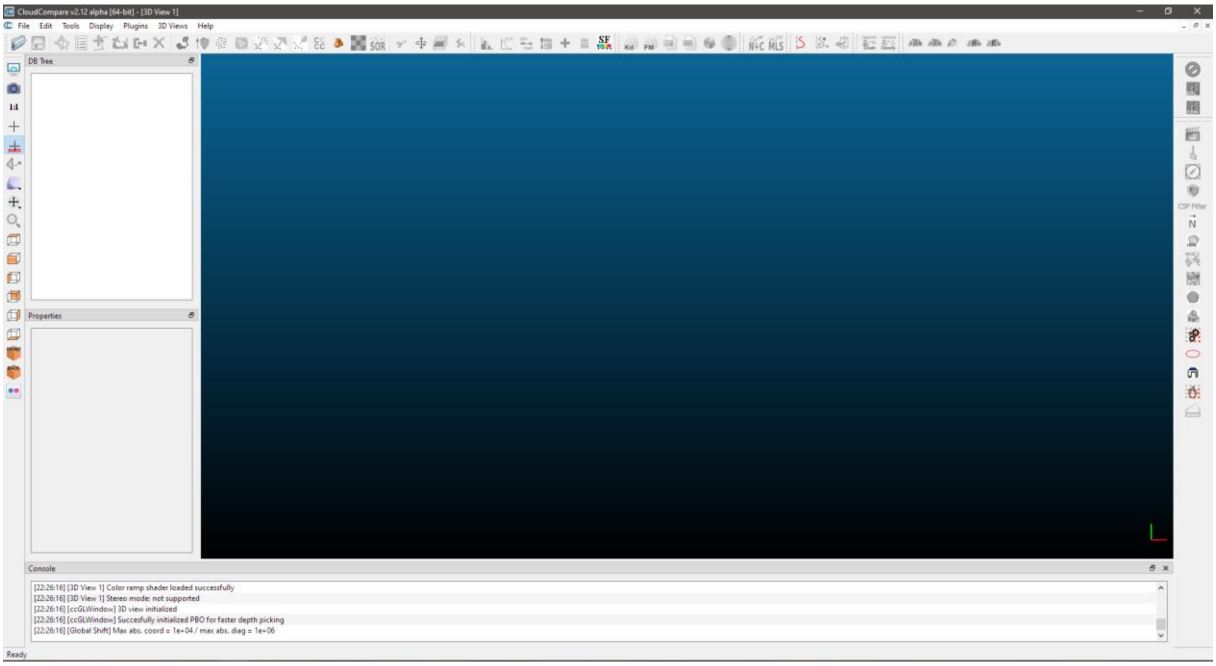


Figure 30 – Screenshot of the empty CloudCompare interface

As with PotreeDesktop, point clouds can be dragged and dropped into the software after which the data is converted and octrees are calculated.

The functionalities of CloudCompare are more extensive compared to PotreeDesktop. Besides basic functionalities for navigation, positioning and manual editing and visualization, the software offers several advanced processing algorithms that allow for, as stated on the website: “registration, resampling, color/normal/scalar fields handling, statistics computation, sensor management, interactive or automatic segmentation and display enhancement.”

4. Results

Following from the previous chapter, this chapter will provide the resulting outcomes.

4.1 Basic digital twin requirements

Scientific literature is divided over the definition of a digital twin, as well as its basic requirements. However, there are various studies attempting to narrow down the variety of conceptions. Therefore, some of these deductions will be addressed in order to provide insights in the basic requirements of a digital twin. Furthermore, based on the examples of digital twin cities presented in paragraph 1.7, these will be supplemented by corresponding characteristics.

Literature

Tao et al. (2018) address one of the main characteristics of a digital twin is that it bridges the physical world and the digital worlds. They base their characterization on research by Glaessgen & Stargel (2012, in Tao et al, 2018), which formulate three components of a digital twin: A physical product, a virtual product and a link between those two. Hereby, the virtual component mirrors the physical component in a virtual environment. This principle is shown in Figure 31.

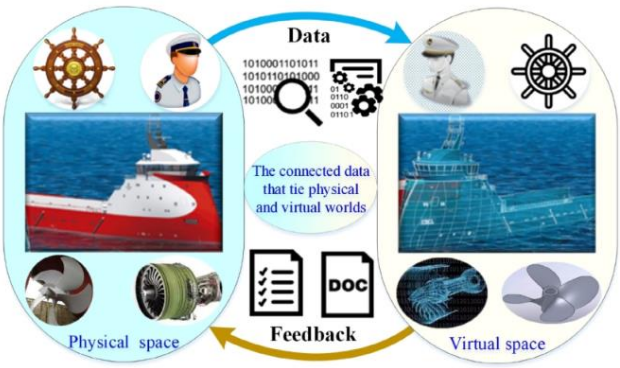


Figure 31 – General principle of a digital twin (Source: Tao et al., 2018)

Furthermore, they address six steps in building a functional digital twin:

1. Build the virtual representation of the physical product
2. Process data to facilitate design decision-making
3. Simulate product behaviours in the virtual environment
4. Command the physical product to perform recommended behaviours
5. Establish real-time, two-way, and secure connections between physical and virtual product
6. Collect all kinds of product-related data from different sources

Moyne et al. (2020) also deduced the basic principles of a digital twin to certain characteristics. Hereby they formulate the following properties: It is a replica of a real thing, it exists in the cyber world, it has a purpose within the context of its real counterpart, it uses models to achieve this purpose, some level of subject-matter is incorporated, data is used to maintain synchronization with its real counterpart.

Although these properties are still broad and multi-interpretable, they do provide a basic understanding of the essence of a digital twin. Hereby, they do address that the context in which a digital twin is created determines the specific needs and functionalities. Therefore, in order for a digital twin to be effective, the domain in which the digital twin is applied should be specified.

Furthermore, the importance of maintaining the digital twin is addressed, stating that methods for doing so should be part of the digital twin. This requires a certain degree of intelligence within the digital twin to keep itself up to date with the physical counterpart.

Shao & Helu (2020) researched various perspectives on digital twins. Considering the definition of a digital twin, different terms are used to do so. Most common are terms as digital or virtual representation and model. Furthermore, viewpoint, fidelity and temporal integration were assessed. The outcome provides three key factors that determine a digital twin, being application, viewpoint and context.

They argue that the digital twin's specific application constitutes if real-time or offline updating will suffice. Besides, it determines which aspects need to be included. Moreover, they argue that accuracy determines a digital twin's usefulness, and not its complexity. Based on the viewpoint, a choice needs to be made what kind of digital twin is preferred. As this viewpoint depends on the application in which a digital twin will be established, a digital twin can either be a product twin, a process twin or a system twin. The third key factor, context, determines which form is used to present the digital twin. For instance, as addressed, one can choose whether or not to use a visualization to provide information.

Resulting from these researches, the following requirements of a digital twin can be formulated:

1. The digital twin is a representation of a real object, system or process
2. It is built for a specific reason (Context)
3. The digital twin provides access to relevant additional data (Semantics)
4. The digital twin provides certain functionalities
5. The digital twin needs to be up to date (actuality)

Considering the quality of the 3D city model, which in this case directly represents the digital twin, Krämer et al. (2007) define six criteria on which this can be measured, being positional accuracy, completeness, semantic accuracy, correctness, temporal conformance and logical consistency. When meeting these criteria, the digital twin provides a sufficient representation of reality in terms of its usability and applicability.

Digital twin examples

Paragraph 1.7 has presented several examples of 3D city models and digital twin projects in the Netherlands. Several corresponding characteristics can be identified among the different examples. Firstly, it stands out that a 3D representation of reality is essential in producing a digital twin city. However, the way in which this 3D representation is obtained varies. Whereas some initiatives prefer BIM or CAD models, others prefer to use height data for vertical extraction of building footprints. Only the city of Groningen seems to aim at using point cloud data directly as input for the 3D representation.

Secondly, the availability of several data sources is mentioned in the majority of initiatives as part of the digital twin. This can be specific sensor data, open data or other forms of linked data.

A third characteristic that arises from the initiatives is usability and functionality. Whereas some digital twin designs aim specifically at the users, others only address the need for data monitoring or analyses functionalities. This also relates to the availability of additional data that is incorporated in the digital twin, as an important functionality of a digital twin is to query the 3D model in order to gain more knowledge of the object of interest.

Lastly, a common theme among several initiatives is temporality, using the term ‘real-time’ in both data collection, data integration and monitoring. This means there is a need to keep the digital twin as close to reality as possible in terms of providing up to date information.

To summarize, the following requirements can be distinguished:

1. The digital twin is represented by a 3D model (Visualization)
2. Several data sources are incorporated (Semantics)
3. The digital twin provides certain functionalities (Interaction)
4. The digital twin is up to date (Actuality)

4.2 Viewing the point cloud data

Using Potree Desktop, AHN3 data is easily dragged and dropped into the software interface. In this case, tile 07DN1 is used, which includes the Groningen city centre. Using the 2.0 Potree Converter to convert the 1.9 GB LAZ file takes approximately 7 minutes and 20 seconds, Given the point cloud consists of 434.452.702 points.

Initially, the point cloud appears as all white. Besides, the points are depicted as squares. However, these visual properties can easily be adjusted by selecting the file name in the scene tab, after which several scene visualization options become available. Figure 32 shows the initial point cloud (top), coloured by classification (bottom left) and coloured by elevation (bottom right).

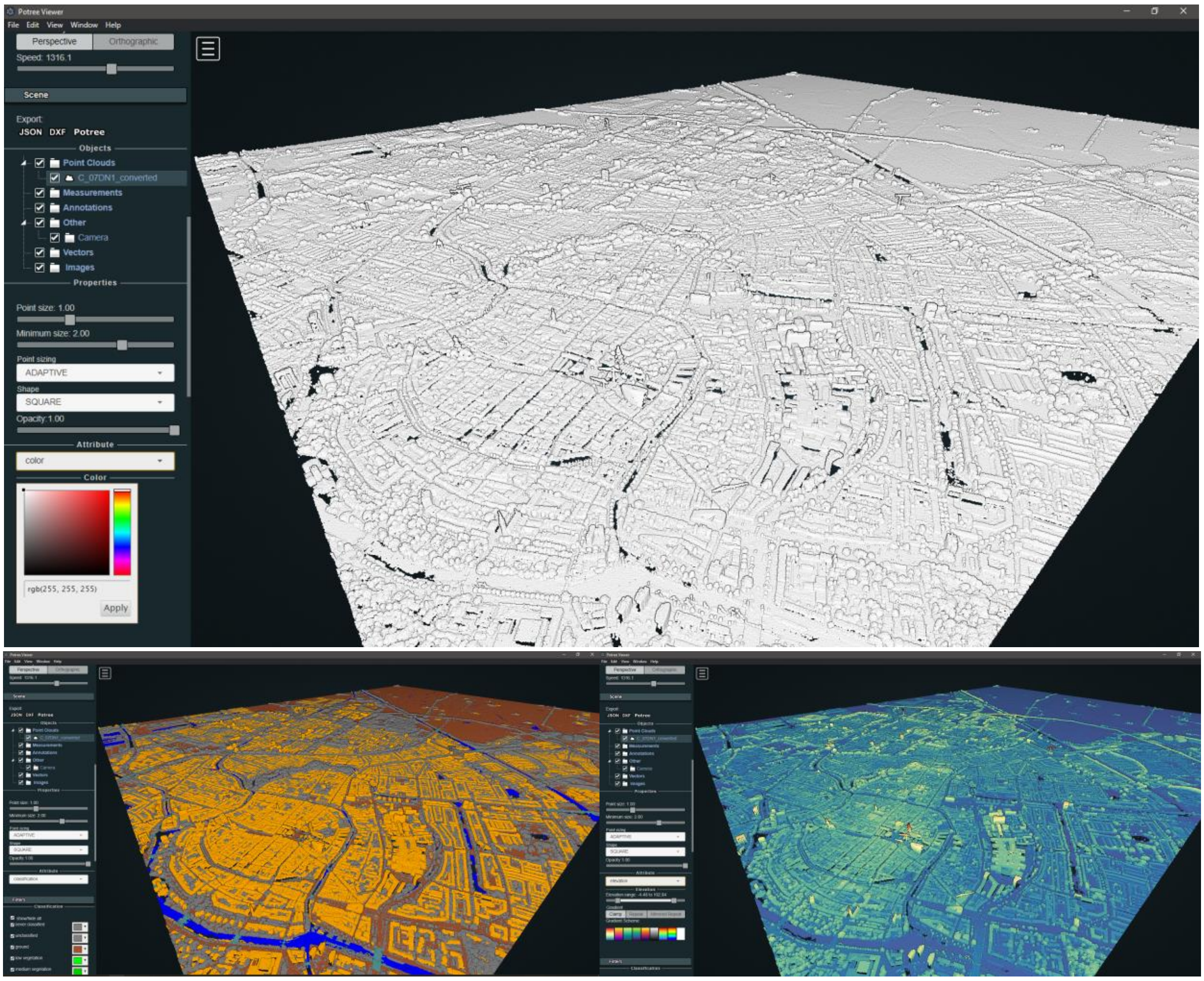


Figure 32 – AHN3 point cloud visualized three ways in PotreeDesktop

Geotiles also provides the same point cloud coloured based on RGB values derived from aerial photos. When dropping the 2.7GB LAZ file in the PotreeDesktop viewer and using Potree Converter 2.0, however, the point cloud is not converted and nothing is visualized. Potree Converter 1.7 on the other hand does respond and takes approximately 24 minutes and 20 seconds, which is significantly longer. Figure 33 shows the result.

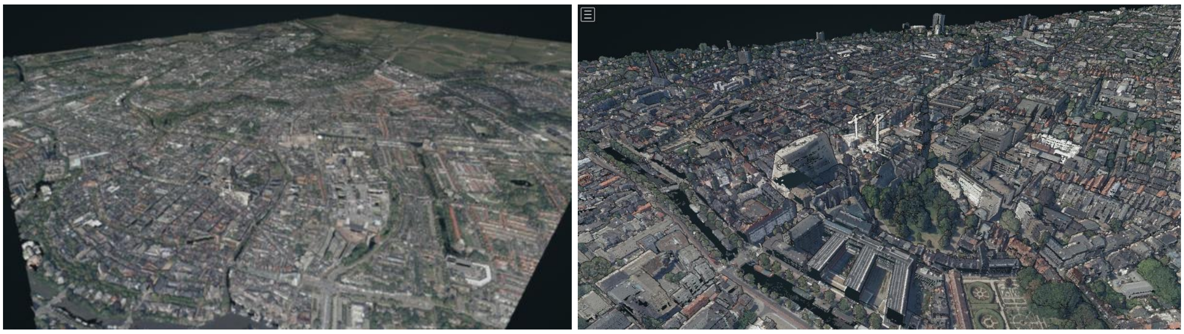


Figure 33 – ALS point cloud of Groningen city centre, coloured by aerial photos (Source: AHN3)

4.3 Combining ALS and TLS data

As addressed in chapter 2, arial and terrestrial point cloud capturing methods both have their advantages and limitations regarding realistic representation of the physical environment. Whereas ALS methods are able to accurately capture rooftops, TLS methods perform better in accurately capturing building facades and smaller objects. Combining these techniques can result in a more complete representation regarding urban environments.

In CloudCompare, AHN3 data of Eindhoven is combined with the TLS point cloud data of 'Stratumseind'. However, some intermediate steps had to be taken to be able to do so. First, the amount of points in the 'Stratumseind' dataset had to be reduced, as the software had trouble with performing computations on the initial point cloud consisting of 257,401,153 points. Using the subsampling tool, the amount of points was reduced to approximately 10% of the initial point cloud, resulting in a point cloud consisting of 25,740,115 points. Secondly, the AHN3 point cloud was cropped approximately to the extent of the TLS point cloud. Using the segment tool, a rectangular selection was made to approximately select the extent of the AHN3 point cloud overlapping with the 'Stratumseind' point cloud. The third step was to align both point clouds vertically. Whereas the point clouds were aligned on the x and y coordinates, a vertical offset had to be corrected. Figure 34 shows this offset.

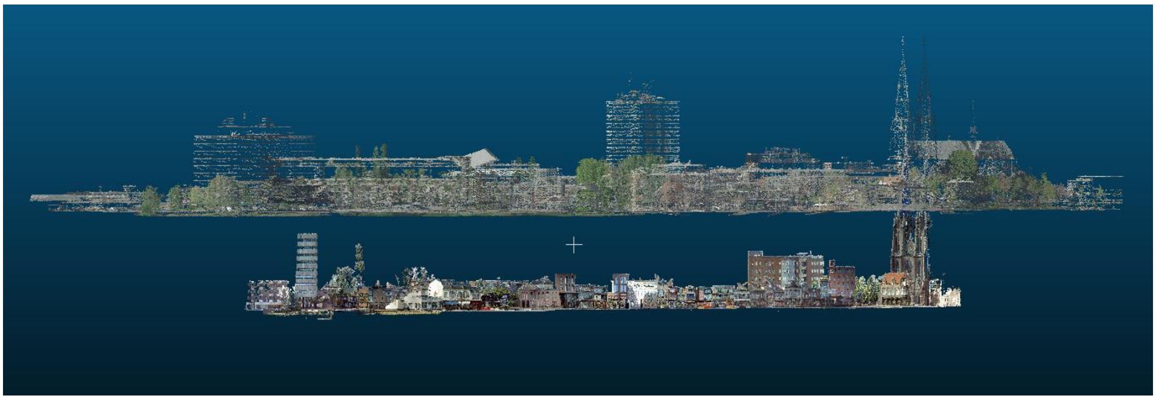


Figure 34 – Vertical offset between AHN3 (top) and Stratumseind (bottom) point cloud

The only tool in CloudCompare for automatically aligning the point clouds is the ‘Fine Registration (ICP)’ tool. Based on the Iterative Closest Point (ICP) algorithm, one point cloud is kept at place while the other point cloud is fitted to match the reference point cloud. After doing so, the result can be presented. Figure 35 shows a top view of the TLS point cloud. Although the streets are visible, hardly any rooftops are captured. Figure 36 shows the combined result.

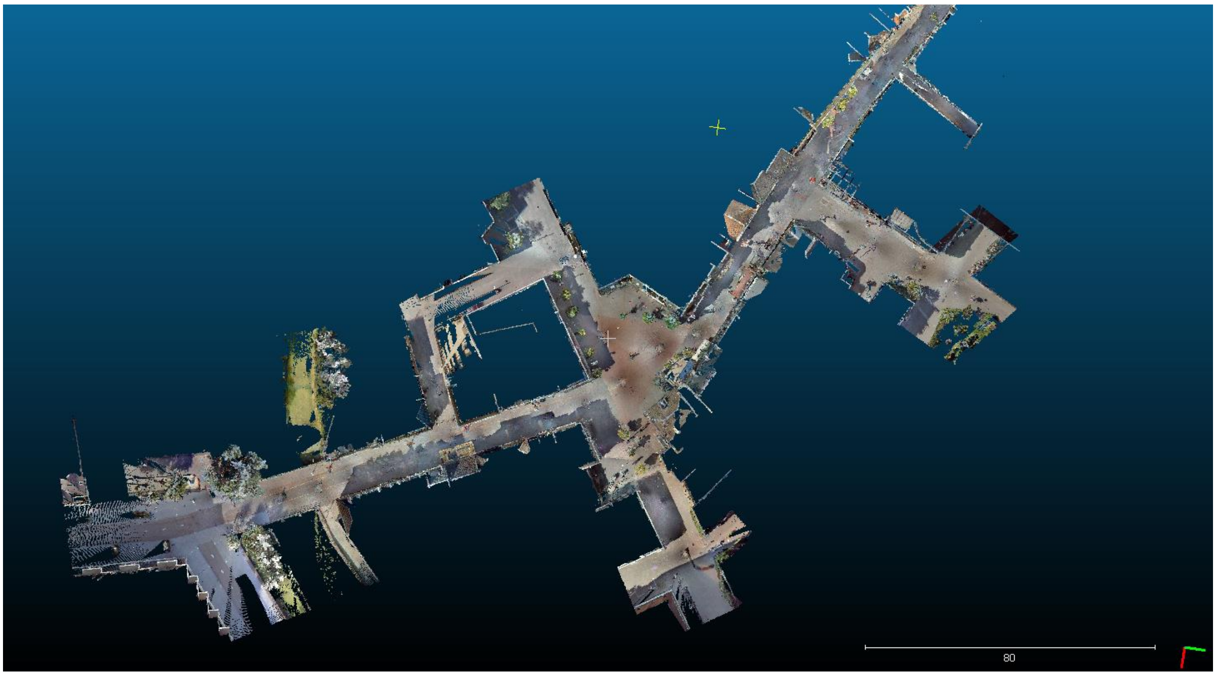


Figure 35 – Top view on the TLS point cloud of 'Stratumseind'

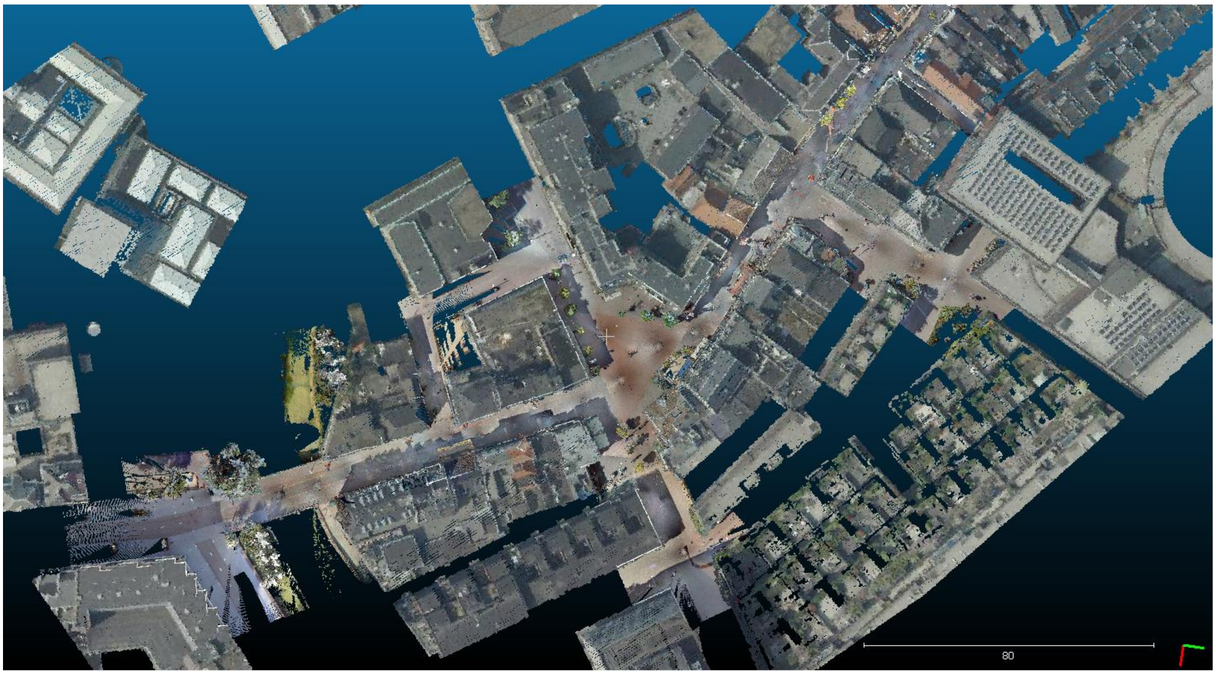


Figure 36 – Top view of the combined result

With regard to facades, Figure 37shows the AHN3 point cloud. In order to provide a clearer view, only the points representing buildings are extracted based on the internal classification of the AHN3 point cloud. Figure 38 shows the combined result from a birds-eye perspective.

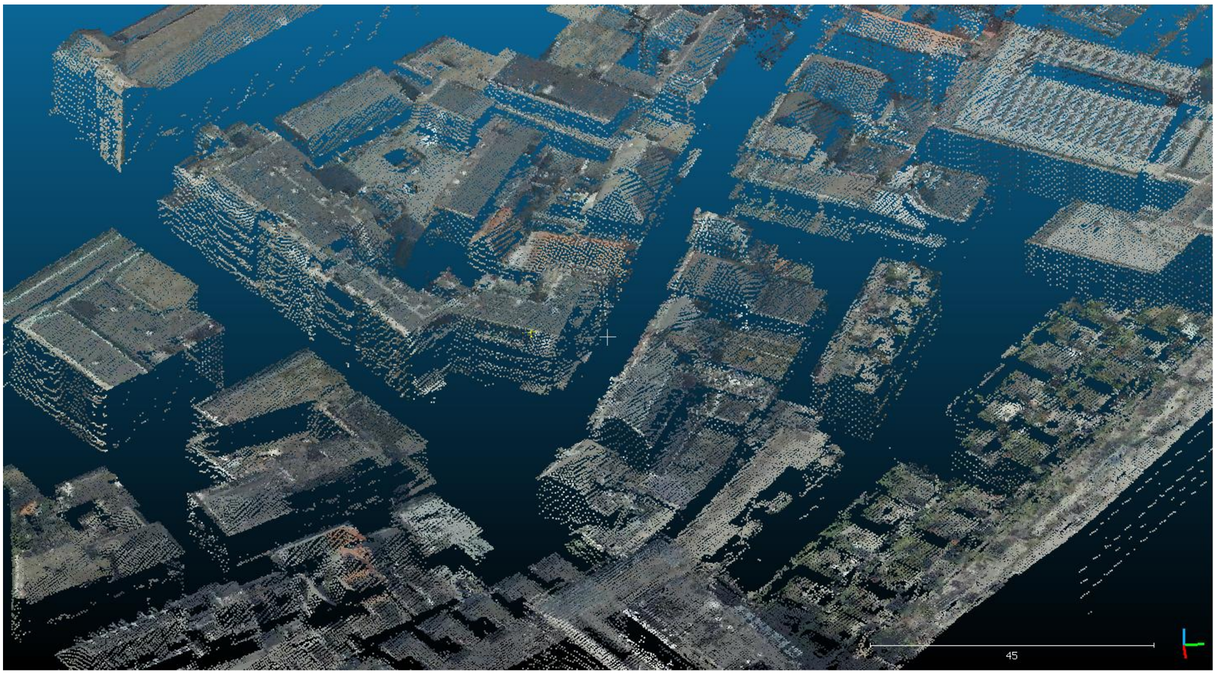


Figure 37 – Birds-eye view on the AHN3 point cloud

Figure 38 – Birds-eye view on the combined result

4.4 Change detection

As described in paragraph 3.3, change detection on point cloud data can be based on several techniques. However, point cloud to point cloud comparison is the most straight forward. In light with the idea that the point cloud representing the digital twin can be easily updated by obtaining new point data of changed areas, a simple point cloud to point cloud comparison has been done. First a visual comparison has been done using PotreeDesktop. For this purpose, AHN2 and AHN3 point clouds of the area near the Erasmusbrug in Rotterdam, also referred to as 'Kop van Zuid', have been used as this area has been under development in the past decade. From the Geotiles website, tile 37HN1 has been selected. Figure 39 and Figure 40 respectively show the AHN2 and the AHN3 point cloud of the 'Kop van Zuid' area.

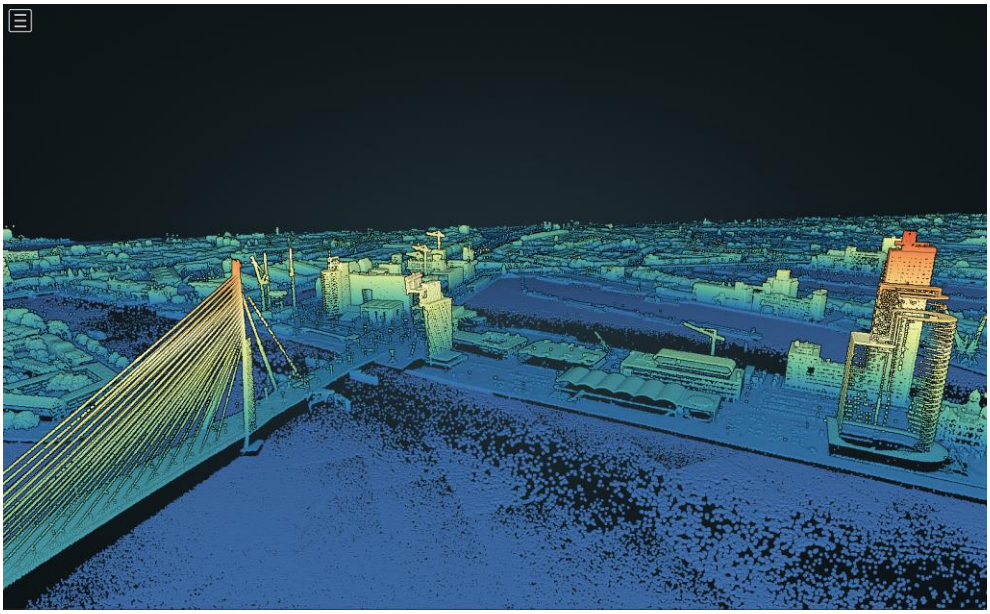


Figure 39 – AHN2 view on the Kop van Zuid area

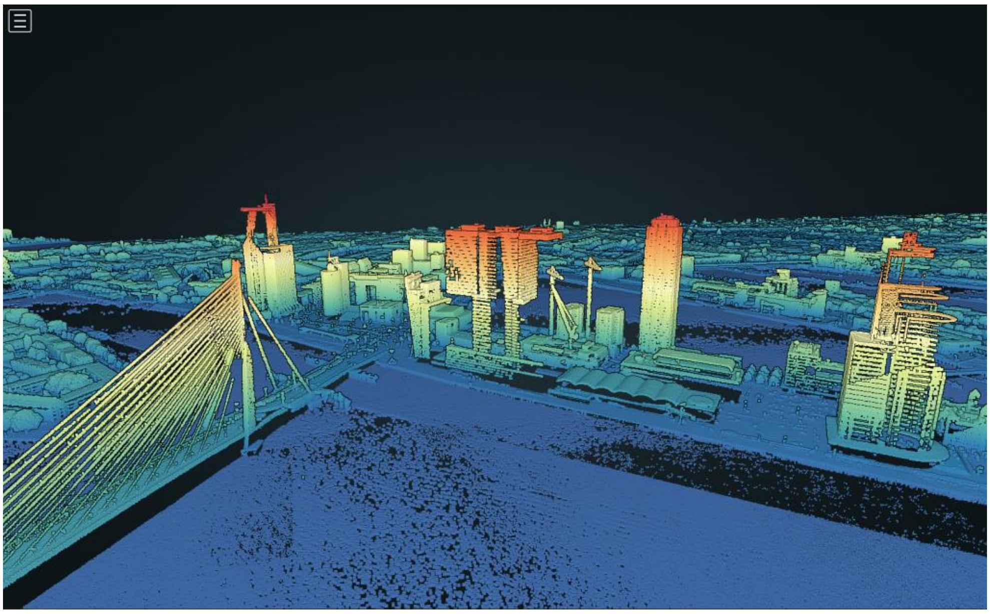


Figure 40 – AHN3 view on the Kop van Zuid area

Overlaying these point clouds while assigning each point cloud a different colour leads to the visual comparison shown in Figure 41.

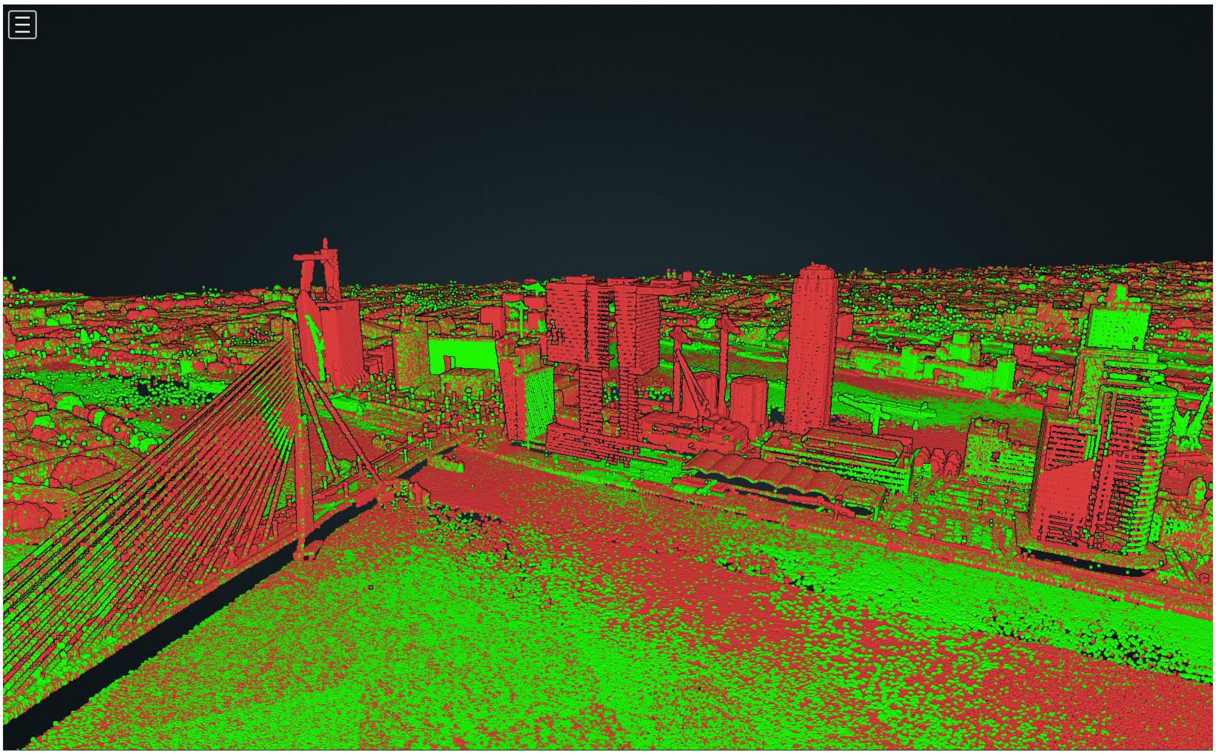


Figure 41 – Simultaneous visualization of AHN2 and AHN3

This overview shows the AHN2 point cloud in green and the AHN3 point cloud in red. In order to provide a more precise comparison, however, CloudCompare is used to compute the actual differences. Using a simple point cloud to point cloud computation as described, the absolute distance of 'new' points to the reference point cloud is calculated. Due to the large file extent of the complete 37HN1 tile, sub-tile 37HN1_9 has been downloaded from geotiles.

Both smaller AHN2 and AHN3 datasets are coloured and respectively consist of 17.359.559 and 11.326.896 points. Figure 42 and Figure 43 show the AHN2 and AHN3 point cloud in CloudCompare.

Figure 42 – AHN2 point cloud of the Kop van Zuid area

Figure 43 – AHN3 point cloud of the Kop van Zuid area

By setting the AHN2 point cloud as the reference cloud and the AHN3 point cloud as the compared cloud, the 'Compute cloud/cloud distance' tool compares the point clouds and calculates the absolute distance of 'new' points to the reference point cloud. This information is then written to a scalar field on the comparison point cloud, in this case AHN3, which can be used to visualize the result as seen in Figure 44, showing the initial output of the C2C computation.

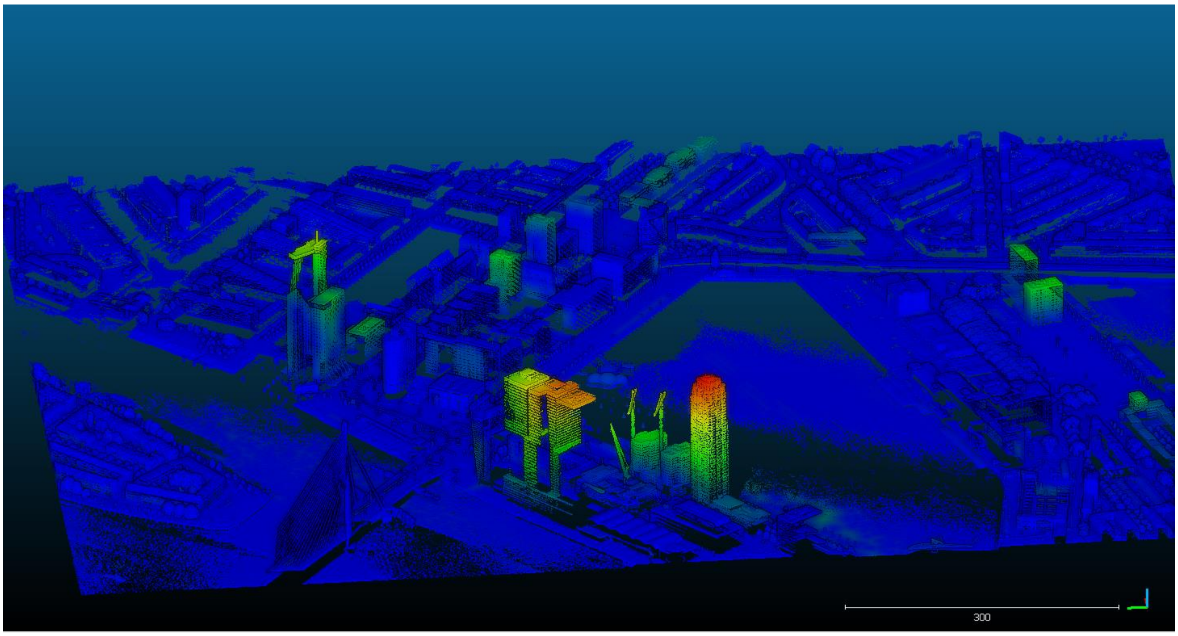


Figure 44 – Initial output of the C2C computation in CloudCompare

Hereby, the points visualized in blue are indicating no change since the absolute distance of those points compared to the reference point cloud is too small to be considered a change. Points visualized in colours ranging from green to red, however, do indicate change. Whereas green points indicate a relatively smaller distance to the reference point cloud, red indicates a higher distance.

5. Conclusions

This chapter will present the conclusions based on answering the sub-question and subsequently the main question of this research. First, the sub-questions will be discussed.

5.1 Point cloud as direct DT representation

The first sub-question was concerned with the extent of which point cloud data can be used directly to represent a digital twin and reads: 'To what extent can a point cloud be used to directly represent a digital twin?'

The first part of this question can be answered based on chapter 2 regarding related work. As is discussed, research by Grasso et al. (2017), Diaz- Vilariño et al. (2018) and Zhang et al. (2017, 2021) show the properties of point clouds make them suitable for usage as an as-is representation of the real world. Led by technological advancements both in the fields of LiDAR and photogrammetry technologies, the precision, accuracy and detail with which point clouds can be presented have increased enormously.

Based on the requirements of a digital twin as discussed in paragraph 4.1, a digital twin needs to provide a visual representation, provide access to additional data, allow for functionalities regarding interaction and querying and represent a certain degree of actuality. This will be further elaborated on in the following paragraphs.

Visual representation

One of the advantages of point cloud data is that it provides a direct, three-dimensional representation. Nevertheless, the examples of 3D city models and digital twins addressed in paragraph 1.4 (3DBAG, Argaleo, Future Insight, Ecocraft, Rotterdam 3D) show that point cloud data is used to create a simplified model of reality.

Although it has been argued that a 3D representation has more value when having a higher resemblance to reality, the majority of the 3D models lack this realistic visualization. By comparing point clouds of the AHN and the municipality of Eindhoven with the existing digital twin representations and imagery, it becomes clear that point cloud data is perfectly able to represent reality quite accurately.

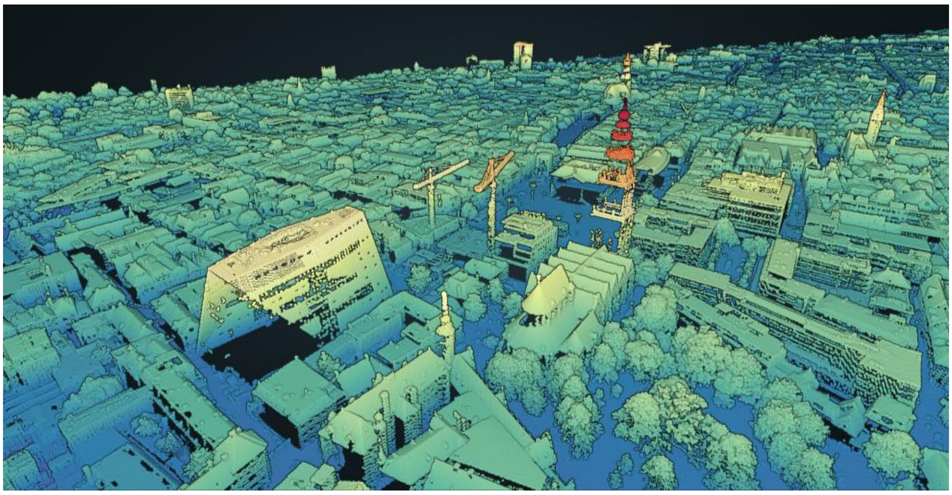


Figure 45 – ALS point cloud of Groningen city centre (Source: AHN3)

Starting with AHN3, Figure 45 shows that buildings and structures are easy to distinguish while providing direct visual information on relative heights. Considering the point cloud is visualized using elevation for colouring, the area is still very recognizable.

However, a more realistic representation is provided by combining the point cloud with aerial imagery. By doing so, the point cloud represents the world closer to what is observed with the human eye in real life. This is shown in Figure 46, displaying the same point cloud as Figure 45, although visualized based on the RGB values derived from aerial photos.

Figure 46 – ALS point cloud of Groningen city centre, coloured by aerial photos (Source: AHN3)

However, as can clearly be seen, buildings are lacking points at facades. Especially the larger buildings on both sides of the construction cranes show huge gaps in the data, while rooftops are almost represented as they are. The explanation lies within the altitude and flight direction of the aerial vehicle carrying the LiDAR scanner, as well as the angle at which the data is captured.

While the lack of detail on these aspects can be considered a limitation of ALS point clouds, the opposite is true for TLS and MLS point clouds. As the point cloud data is captured at a much closer range and at street level, building facades and smaller objects are especially detailed. Figure 47 shows a view from the TLS point cloud of part of the 'Stratumseind' area in the city of Eindhoven.

Figure 47 – View from TLS point cloud (source: Municipality of Eindhoven)

As can be seen, details regarding colour, street furniture, trees and relief differences on building facades are depicted very accurately. As comparison, a Google Street View image from approximately the same location is provided in Figure 48.

Figure 48 – Screenshot from Google Street View (Source: Google)

Although the capturing dates of the ALS point cloud and the Google Streetview imagery differ, they do show a similar scene, in which objects and buildings are directly recognizable.

Using MLS point clouds, the same level of reality can be accomplished as is shown by Cyclomedia (2018). Providing a 360 degree LiDAR point cloud as well as the simultaneously captured imagery shows how good the point cloud is able to represent the world in a photorealistic way. Figure 49 shows the imagery captured at 'De Dam' in Amsterdam, while Figure 50 shows the corresponding point cloud. Nevertheless, the 360 degree point cloud does not provide any interactive functionalities, thereby providing no direct added value over a panoramic photo, for instance.

Figure 49 – Cyclorama image by Cyclomedia (Source: Cyclomedia, 2018)

Figure 50 – Mobile LiDAR scan of the same area (Cyclomedia, 2018)

However, although providing a realistic experience at ‘street level’, rooftops are likely to be poorly represented. By solely providing ALS or TLS/MLS point clouds, it is likely for the representation to lack in terms of completeness. However, combining these methods in order to fill the data gaps caused by their limitations is a solution to this issue. As paragraph 4.3 shows, ALS and TLS point clouds of the same area can be quite easily combined in order to provide a complete representation.

Furthermore,

Limitations of current representations

In contrast, the current way of 3D representation in Dutch digital twins as discussed in paragraph 1.4 shows that there are a lot of downgrades when using point cloud data. For example, 3DBAG and Rotterdam3D are used to assess the representation in terms of accuracy. In the 3DBAG, information on buildings and addresses is available, while objects are depicted in three-dimensional shapes representing those objects. These building heights are retrieved from AHN data, which is point cloud data. Instead of using the point cloud data to represent the objects, only height information is used to vertically extract objects from their ground contours.

The online viewer https://3dbag.nl/en/viewer allows the user to set three different levels of detail, being LoD 1.2, LoD 1.3 and LoD 2.2. Examples of what this looks like is shown in Figure 51, Figure 52 and Figure 53, displaying the Rotterdam central station area.

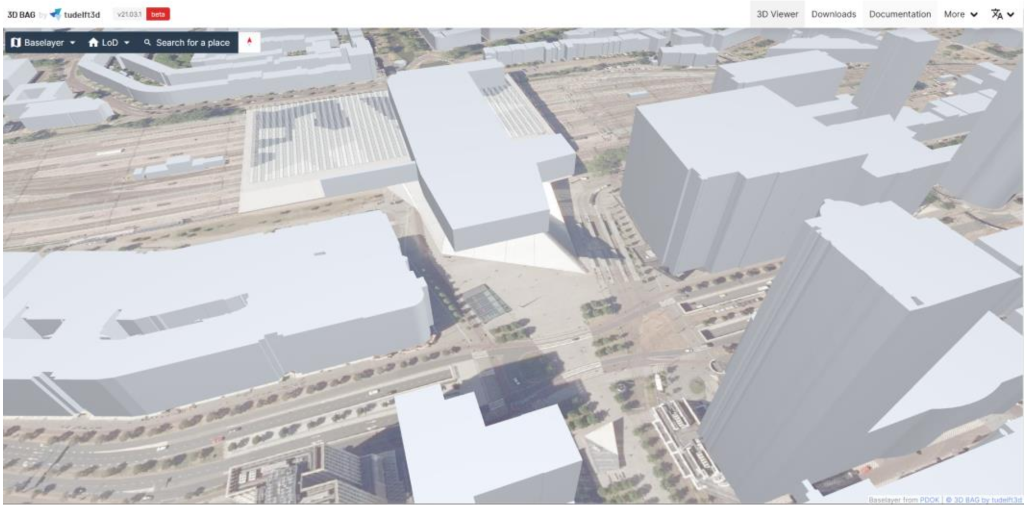


Figure 51 – View of 3DBAG in LoD1.2 (Source: 3DBAG)

Little to no detail is included apart from building contours and heights. Most rooftops are represented as flat surfaces, while facades show no details or relief.

Figure 52 – View of 3DBAG in LoD1.3 - (Source: 3DBAG)

The LoD1.3 representation already provides more detail, which is evident at rooftops and facades, although still being an extremely simplified representation.

Figure 53 – View of 3DBAG in LoD2.2 (Source: 3DBAG)

The third possible option for users of the 3DBAG is to represent the objects in LoD2.2. Even more detail is provided. However, it still lacks essential detail to accurately represent reality, apart from the objects being depicted as grey blocks without any colouring or texture.

The most remarkable, however, is that the building in the middle should represent the Rotterdam central station. The central station building is quite an architectural challenging building to accurately model in 3D. Figure 54 shows a Google Street View image of what the entrance of the building looks like. Even the most detailed representation in the 3DBAG viewer, LoD2.2, does not provide any detail regarding the entrance, although this can be explained by the limitations of ALS point cloud acquisition.

Figure 54 – View in Google Street View on Rotterdam Central Station (Source: Google)

Given the fact that the representation of objects is based on point cloud data, the results are rather poor in representing reality as compared to the possibilities of accurate representation discussed previously. Although the municipality of Rotterdam has developed their own 3D city model, the issues remain the same. Compared to the 3D BAG, the Rotterdam 3D model does allow for texturizing the objects.

While the basis of the 3D model is similar, being AHN point cloud data, aerial photos are used to texturize objects and thereby providing more visual detail. Nevertheless, details in terms of relief on both roofs and facades is still missing.

Figure 55 – Texturized LoD2 model of the Rotterdam central station building (Source: Rotterdam 3D)

A possible problem in representing objects that do not directly have a ground-based shape, is the way in which the modelling process is executed. As with the Rotterdam central station building, the Euromast provides an even better example. Figure 56 shows the representation of Euromast in Rotterdam, which is quite an iconic building, in the 3D BAG viewer.

Without any knowledge of the building, one would think this building has a relatively wide base from the ground upwards, narrowing towards the top.

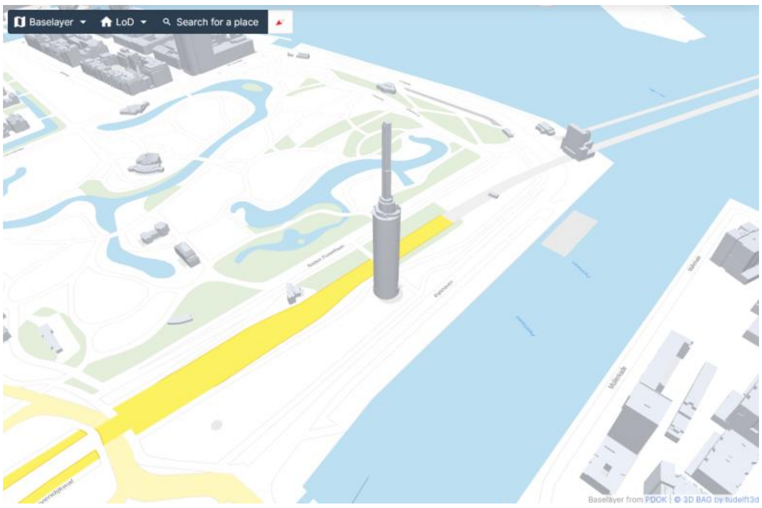


Figure 56 – Representation of the 'Euromast' in 3DBAG (Source: 3DBAG, https://www.3dbag.nl/)

This can be explained by the way the modelling algorithm works, which models the object from top to bottom. Hereby the algorithm assumes that the contour of the roof corresponds with the contour of the building's 2D footprint, after which the facades are modelled downwards. Although based on point cloud data, the representation is quite far from reality and also from what can be seen in the AHN3 point cloud from Figure 57.

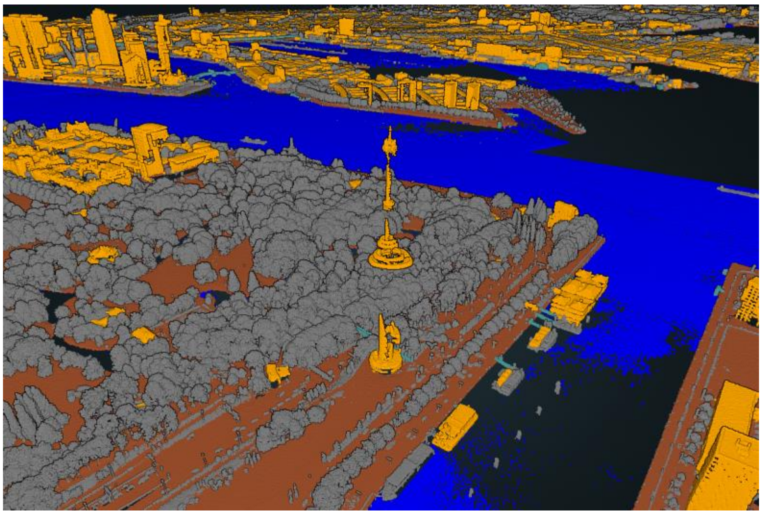


Figure 57 – Representation of the 'Euromast' in AHN3 (Source: AHN3)

Despite having limitations on its own, the AHN3 data does show the approximate shape of the building. The Rotterdam 3D model, on the other hand, does provide a realistic representation as seen in Figure 58. Although still being a somewhat simplified representation, the shape resembles reality to a greater extent.

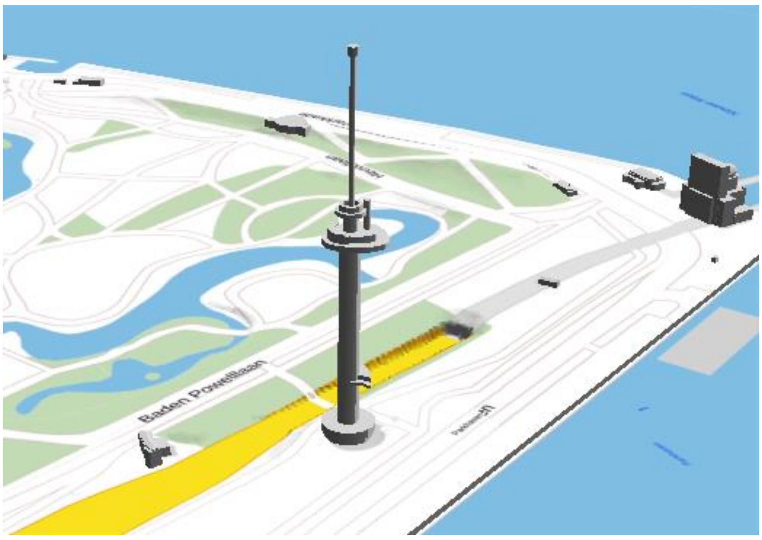


Figure 58 – Representation of the 'Euromast' in Rotterdam 3D (Source: 3D Rotterdam, https://www.3drotterdam.nl/)

This shows that, although point cloud data may not directly be used for representation, it can still aid the modelling process.

Functionality & Interaction

Besides the visual aspects, interaction with the data is also an essential element of a digital twin. The previous paragraph shows the ability of point clouds to accurately represent a city in 3D, whereby the major advantage is that the point cloud can be used as is. However, merely providing a point cloud as geometric model does not meet the basic requirements of being used as a digital twin. Especially considering the functionalities needed within a digital twin to provide added value over displaying a visual representation.

Although complex digital twins for specific systems require a variety of (real-time) data inputs, point cloud data itself is already able to contain sufficient information without the need for additional data sources. Whereas showing a point cloud as a visual representation does not fulfil the requirement of a digital twin as such, being able to navigate through the point cloud from a user perspective can.

The practical aspects of directly using point cloud data in representing a digital twin relate to the way in which one can interact with the 3D representation. Hereby, basic functionalities as positioning and orientation aid in exploring the 3D environment, while more advanced functionalities as measurements, calculations and manual adjustments or modifications aid in application specific analyses. Hereby, the availability of easy to use software is essential. As discussed in paragraph 3.2, open-source software like Potree and Cloudcompare are freely available. Basic understanding of software installation makes these programs appropriate solutions for a variety of possible users, both beginner and expert. Besides, since they both are open-source software, there are ongoing improvements based on user experiences. The Potree environment, for example, provides a variety of functionalities regarding navigation as shown in Figure 59.

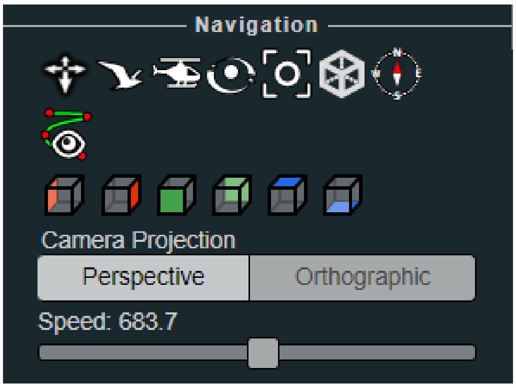


Figure 59 – Navigation tab in PotreeDesktop

The different navigation options make it easy to choose a preferred method to control viewing and moving directions. Depending on the chosen method, these actions can be performed using keyboard arrows, the computer mouse or both. What stands out is the fast rendering of the point cloud due to the conversion when first loading the data.

Software and viewers specially dedicated to point cloud data, such as Potree, enhance one of the major advantages point cloud data possesses: the ability to directly interact with the data. With the increasing availability of such viewers and a growing support for point cloud data in existing software, point cloud data offers serious benefits over representations based on extensive modelling techniques that, after modelling, often result in unrealistic, simplified representations.

5.2 Point cloud change detection

The second sub-question reads '*To what extent can point cloud data be used for change detection in a physical environment?'.* As is discussed in paragraph 2.3, various 3D change detection methods have been researched and developed, also so for point clouds. In principle, the most basic form of change detection on a point cloud is by comparing two point clouds of the same area, captured at different points in time. Despite the possible differences between two point clouds regarding the accuracy, precision and technical specifications of capturing devices, generally two scenarios are possible: 1. Points represent an object that was not there before, 2. Points that represented an object before are not there anymore.

Contemporary LiDAR scanners and high quality cameras are becoming smaller and more versatile, thereby expanding the possibilities of on sight surveying. This is essential for detecting change in physical environments. As the urban environment is changing faster while becoming more complex, the increasing versatility and quality of surveying equipment enhances the process of capturing these environments.

Point clouds allow for easy positioning and navigation, thereby providing several possibilities of exploration. Using this exploration possibilities, the environment can be easily inspected. Especially when two point clouds of the same area captured at different points in time can be accessed, which is the case with AHN, one can easily compare them visually when put next to each other.

Mere visual comparison of the two point clouds leads to the conclusion that several new buildings have appeared that were not there before. Simultaneous visualization of the point clouds in Potree, whereby the AHN2 data is displayed in green and the AHN3 data in red, even more so provides insight in where changes have drastically occurred. This is enhanced by the interactive possibilities of the visualization in Potree. By looking at the point clouds from different perspectives, one can determine if buildings are indeed 'new', or that gaps in the individual data sets are complemented. Figure 60, for example, shows the same buildings from different perspectives.

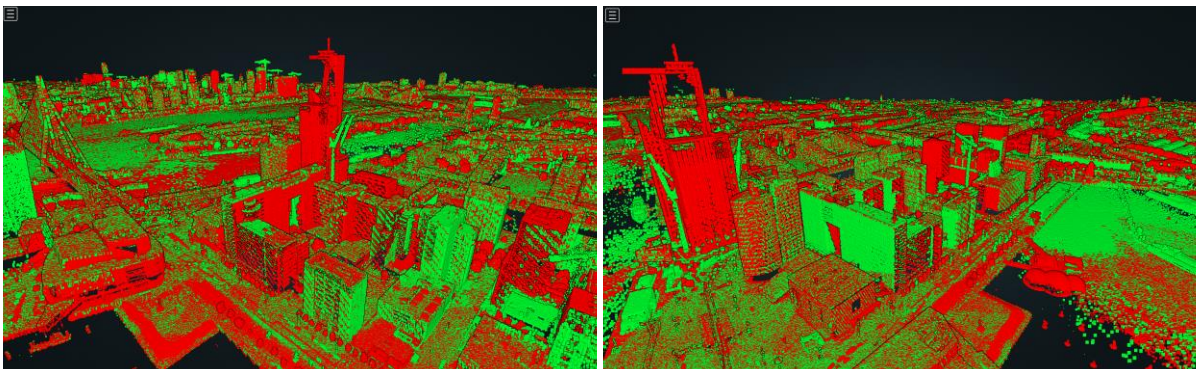


Figure 60 – Simultaneous view of AHN2 and AHN3 point cloud in Potree

In general, interaction is a major advantage of point cloud data, whereas it can easily be visualized in the first place, while also allowing for changes in perspective.

However, this method only provides a visual estimation of possible changes. Nevertheless, overall changes can be quite easily detected based on direct comparison, after which specific objects can be observed in more detail to verify if the detected changes are valid. Exact changes, however, cannot be detected by mere visual comparison despite the ease of interaction with point cloud data. More advanced software is necessary for doing so.

In CloudCompare, using the 'compute cloud/cloud distance' tool, changes can be visualized more precise. As the outcome of the cloud to cloud computation shows, this method provides a much better understanding of changes in the physical environment.

Although the initial result is presented as a colour scale reflecting the absolute distance of 'new' points to the reference point cloud, it can be interpreted differently. By extracting the 'new' points based on their distance, they can be visualized more obvious. Figure 61 shows and Figure 62 show the reference AHN2 point cloud in RGB colours, with the new objects from the AHN3 point cloud coloured in green.

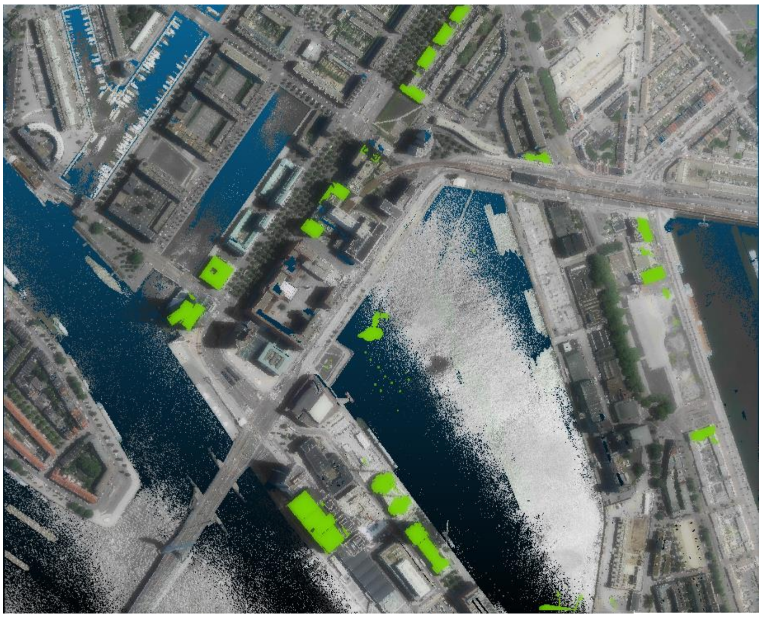


Figure 61 – Top view of change detection result

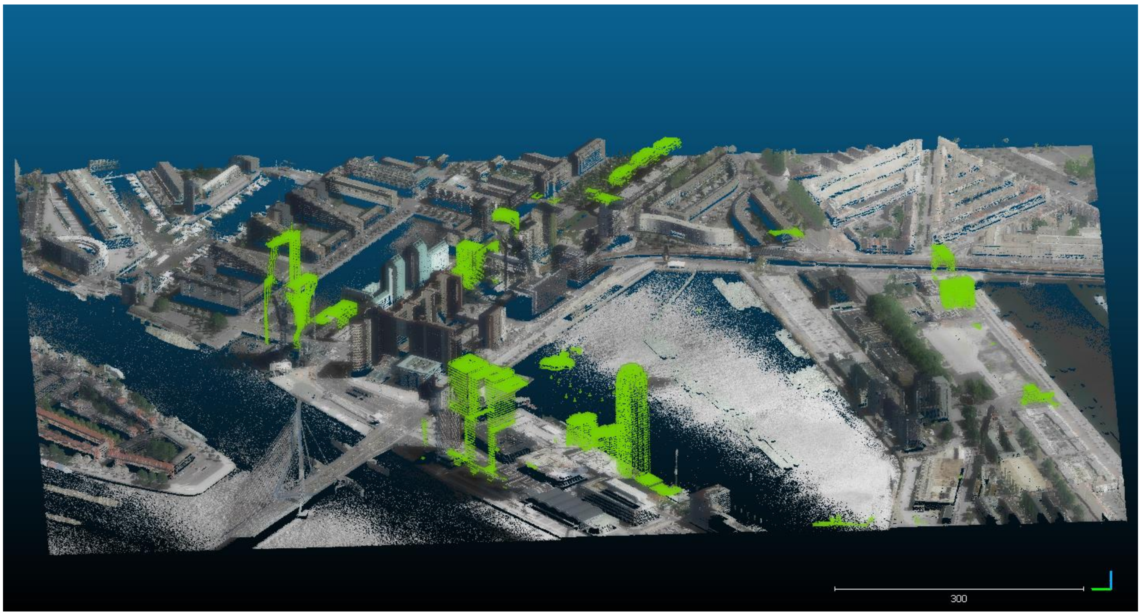


Figure 62 – Birds-eye view on change detection result

Although the result show that point cloud to point cloud change detection can be quite easily performed, the result does not provide any information regarding the quality of the change detection. Besides, prerequisites considering the change detection were not provided as the aim was merely to provide general insights, hence using the default settings in CloudCompare.

Nevertheless, when performing change detection, it is important to consider when changes do indeed need to be marked as such. In order to anticipate on false positives regarding changes, a threshold should be determined. By setting a change detection threshold, points are filtered out that do not correspond with the reference point cloud although representing an unchanged object or area. Factors that determine the threshold for change detection can be based on pre-defined preferences or on properties of the data. Pre-defined preferences can relate to physical characteristics regarding objects of interest (e.g. building height). When determining the threshold based on data properties, two main factors can be of interest, being the point density and registration quality (Xiao et al.; Tsakiri & Anagnostopoulos, 2015). Furthermore, the method for point cloud acquisition should be taken into account. As Taneja et al. (2011) address, laser scanners are quite reliable sources in terms of geometric accuracy whereas image matching techniques are less reliable.

5.3 Updating the digital twin

The third sub-question relates to the practical implications of detecting change and updating those changes to the digital twin. The question reads '*What are the practical implications regarding change detection and frequencies for updating the digital twin?'.* The answer on this question lies within the basic principles of presenting a representation of reality, such as using up to date information and use of standards.

Using up to date information

In order for users to be able to trust a digital twin, using the right data and information as basis for the digital twin is essential. However, this may not always seem the case. An example can be found in a 3D model of the Netherlands featuring building heights, based on the LOD1 model from the Dutch Kadaster. Within an online viewer provided by Webmapper (2018), one can gather information about the height of buildings in the Netherlands. When looking at the 'Kop van Zuid' area, some things stand out considering the height of a specific building.

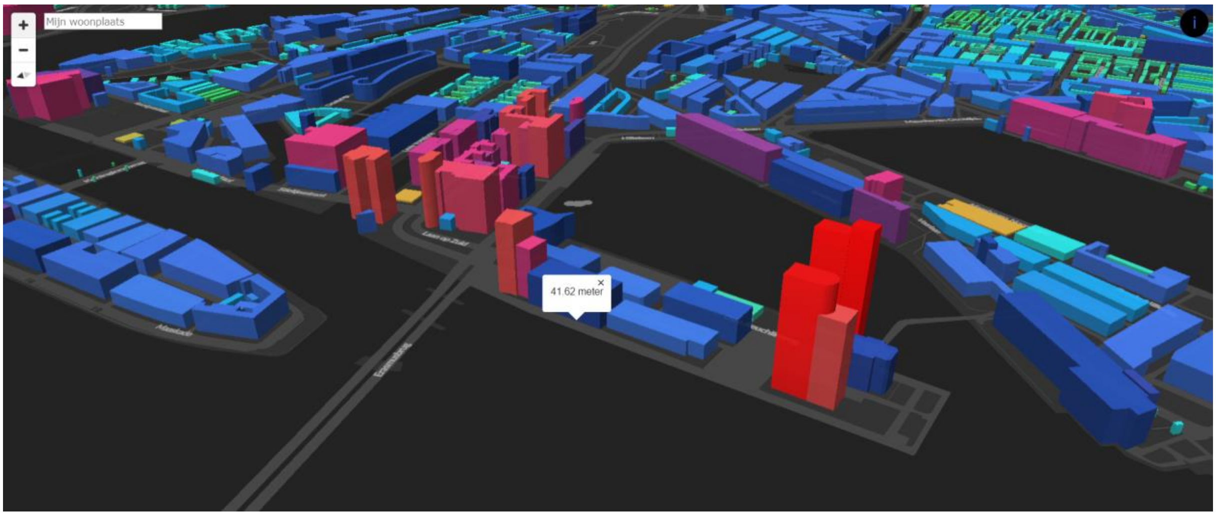


Figure 63 – View on Kop van Zuid area (Source: Gebouwhoogte Nederland)

Figure 63 shows that the building height of the building in the middle is 41.62 meter, whereas in reality that building is 149 meters high. This is problematic since the 3D model can be viewed and used by anyone. Although unlikely, such 3D models could be used in decision making processes. In this case the 3D model will present false information. The practical implications regarding this example relate to the display of false information by insufficient updating of the 3D model. However, by providing the right nuances when presenting the data, it can become clear that the false information is caused by a specific situation.

Furthermore, practical implications regarding updating of the digital twin lie within the integration of additional data. The more integration of different data sources, the more data to be updated when something changes. In other terms, the digital twin becomes more dependent on additional data sources when the amount of data integration increases. This already is the case in the key registrations of the Netherlands, whereas developments are in progress to integrate all separate registrations into one, all comprising key registration. Implications for its usage in a digital twin relate to the amount of integration, while separate registrations need to complement each other instead of providing conflicting information.

This, however, is the case in the 3DBAG. Figure 64 shows an aerial photo of a farm near the city of Delft. The object of interest is the large rectangular building. Whereas, even from an aerial photo, it can be concluded there clearly is a building there, the 3DBAG viewer lacks in representing the object as seen in Figure 65.

Figure 64 – Aerial photo of a farm (Source: Google Maps)

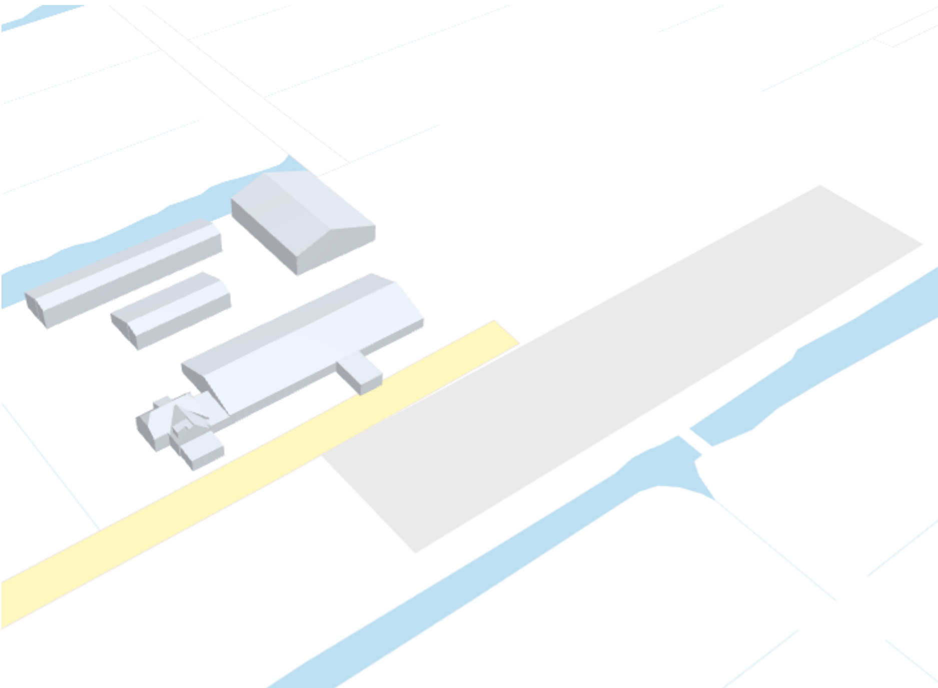


Figure 65 – 3D view of the same farm (Source: 3D BAG)

This discrepancy can in the first place be explained by the fact that such objects are not registered as a building in the BAG. Therefore, although showing a 2D footprint, the object will not be represented both in the registration as in the 3D viewer. Considering the representations of buildings in general, a discrepancy can be explained due to differences in acquisition times. Although the AHN3, on which the 3DBAG is based, is the most recent available version, the data is captured between 2014 and 2019, depending on the area of interest. In the case of the province of Zuid-Holland, in which Delft is situated, the data is collected in 2014. The aerial photo on Google Maps, however, is taken in 2021.

Although this issue might not relate to the previous example, this can be problematic for objects that are registered in the BAG but are not represented in the AHN data. 3DBAG underlines this problem, stating there are arguments against using the AHN for 3D reconstruction since it is "outdated by design", thereby implicating the frequency of data acquisition is too low to keep up with reality.

Updating point cloud data

Although literature is limited on the updating process for digital twins, especially regarding the use of point clouds for direct representation and change detection, methods for doing so can be derived from rather traditional temporal modelling techniques.

In principle, the most effortless method for updating the point cloud representation would be based on change detection. As presented in paragraph 4.4, point cloud to point cloud comparison provides a simple though effective way of determining changes, after which 'new' points can be easily secluded. An obvious though undesirable way of updating would be to replace the existing data by the new data at places where changes have occurred. However, this means access to previous situations is lost. Jones et al. (2020), however, address a key aspect of a digital twin is access to, and interaction with historical data.

Within this perspective, it is desirable to update the point cloud without 'deleting' previous datasets. An essential element herein is temporality. Based on Van Oosterom (2010), a method for integrating time intervals in point cloud data is suggested in order to be able to update the digital twin without deleting 'old' data. In order to do so, it has to be determined at which level of granularity changes are being updated. Four levels of granularity can be distinguished, being the 1) whole dataset, 2) object classes, 3) objects, and 4) attributes. The proposed method is applied to the level of objects.

The concept is as follows. Every object is given two extra attributes with regard to time, being a 'Tmin' and a 'Tmax'. This interval indicates the validity of an object. Applying this to point cloud data, this implicates that a certain level of semantics is required, being at least a classification in which different objects are defined. This is necessary as it requires huge efforts to assign every single point with extra time attributes. In principle, the dataset now contains information on the validity of every object. After a change, e.g. a new building has been detected, the object is provided with time attributes as described.

In order to preserve the old dataset a copy is made of the whole record, after which 'Tmax' is adjusted of the objects that have changed, thereby essentially splitting the dataset into a part that is still considered accurate and a part that is not valid anymore. By dividing the initial data into different datasets based on the temporal information, new data can be incorporated. Hereby, the 'Tmax' of old objects corresponds with the 'Tmin' of new objects. This process can be repeated for new changes, whereby instead of deleting data, merely the 'Tmax' is adjusted to indicate the objects are invalid. This does implicate, however, visualization of the data has to be based on these temporal aspects, thereby requiring functionalities regarding the setting of time.

Change detection and updating frequencies

Keeping the digital twin up to date with reality is one of the most important aspects in order to provide added value over traditional visualization and monitoring processes. However, depending on the context, function and usage of the digital twin, the update frequencies can vary.

However, the context of the digital twin (e.g. application field, intended usage) highly influences the frequency in which new data is collected, which subsequently relates to a great extent to the frequency in which new data is updated. Although these processes can be considered induvial processes, ideally these are subsequential. As Van der horn & Mahadevan (2021) address, a digital twin can be updated at the moment new data becomes available, although these different data may become available at different frequencies.

With regard to the process of updating, Jones et al. (2020) in their research refer to the update frequency as the 'twinning rate', explaining it as 'The act of synchronisation between the two entities and the rate with which synchronisation occurs'. Within their research, they assessed a variety of 92 publications regarding digital twins. Considering the twinning rate, they found that it is generally described as being in real-time. This corresponds with the examples provided in paragraph 1.7 and is confirmed in research by Van der Horn & Mahadevan (2021). Whereas most digital twin and 3D city model developments are aiming at real-time data inputs and updates, the practical implications remain unaddressed. Moreover, when addressing the topic of updates within the digital twin, it is mostly concerned with the linked and additional datasets, rather than the 3D representation itself.

Even if updating the 3D model is addressed, as is the case in Schrotter & Hürzeler (2020), it is only stated that updates need to take place based on predefined intervals, which depend on the application of the digital twin.

However, some support to make a decision on the frequency in which a digital twin is updated can be found in Wildfire (2018). She makes a distinction between reactive digital twins and predictive digital twins. Batty (2018) refers to these as corresponding to 'high-frequency cities' and 'low-frequency cities'. Whereas reactive a digital twin and high-frequency cities rely on (near) real-time data and updates within a day-to-day timeframe, predictive digital twins and low-frequency cities rely on accurate data for longer term planning and decision making.

When determining the update frequency, it is important to consider the importance and necessity of updates, as well as the rate in which physical objects change. In construction monitoring, for instance, it can be desirable to update the digital twin on a daily basis or even more frequent. In the case of monitoring urbanization, monthly or even yearly updates may suffice. This implies that update frequencies can also vary within the digital twin, which is deemed possible using the suggested spatio-temporal approach based on Van Oosterom (2010).

5.4 Conclusion summary

In order to concretize the conclusions presented in the previous paragraph, this paragraph will present a brief summary of those conclusions, which thereby essentially answer the main question. The main question of this research is *'To what extent can point cloud data be used directly in order to act as an up-to-date digital twin?'.* The answer on this question can be derived from the individual sub-questions and will be answered accordingly.

As the conclusions concerning the first sub-question show, point clouds provide an accurate and detailed representation of reality. Although limitations of different acquisition methods are evident, these can be overcome by combining multiple data acquisition methods such as ALS and TLS or MLS. This only enhances the completeness and geometrical accuracy of the representation. Besides, RGB colouring of point clouds based on aerial images (in the case of LiDAR point cloud capturing) or inherently derived from images (in the case of photogrammetry) enhance the realistic representation even more. This leads to fulfilling one of the main requirements of a digital twin, being a realistic visual 3D representation. Furthermore, the topic of semantic enrichment has been addressed. Literature presents several methods for doing so, of which segmentation and classification can be considered essential. Besides, integrating colour and temporal information can be regarded as semantic enrichment as well, which has also been addressed. When this information is integrated, a point cloud can be considered to fulfil the requirement of providing semantics.
When addressing functionality, it has been shown that point clouds allow for direct interaction. Hereby, a point cloud allows for both visual interaction such as positioning, navigation and colour adjustment, as well as interaction in terms of measuring and calculations. Based on these interactive functionalities, a point cloud can be considered to also fulfil this requirement.

With regard to the second sub-question, literature provides an enormous amount of change detection methods, based on 2D as well as 3D data. However, point cloud to point cloud comparison is deemed most logical, as this method does not require any alternative processing steps. This is in line with the direct use of point cloud data as proposed. This research shows that changes can indeed be detected by using a fairly simple point cloud to point cloud comparison method. Although specifications regarding the parameters of the change detection and the threshold for marking differences as actual changes need to be determined in practice, the basic principle has been demonstrated.

The third sub-question relates to the practical implications regarding change detection and updating the digital twin. It is shown that current registrations and available 3D data sources such as BAG and AHN have limitations regarding its actuality, although being considered as the most recent and up to data. If considered for usage in a digital twin, concessions need to be made on how up to date the digital twin can be. In terms of updating the point cloud data itself, a method for integrating temporal attributes is been suggested. Hereby, old data is not deleted but merely marked as 'invalid' based on a time interval. The advantage herein is that access to previous situations is guaranteed. Regarding the frequencies in which the digital twin is updated, literature is rather limited. In line with the contemporary availability of data and rapidity of changes, real-time updating is considered as the ultimate situation. However, relating to updating the 3D model, real time updating poses practical limitations in terms of time, effort and costs. Thereby, the rate in which physical objects change need to be taken into account when deciding on an update frequency.

This leads to answering the main question. When looking at the basic requirements of a digital twin, point clouds are able to fulfil all. Concerning its visual as well as geometrical capabilities, point clouds have a huge potential for being used as-is in representing reality. Besides, classification methods as well as integration of RGB colouring and temporal information enhance basic semantic enrichment, while direct interaction with the point cloud is more or less inherent to the data. These characteristics make that point cloud data is suitable for representing a digital twin. Although currently, modelling and simplification of point cloud data seems to be preferred, technological advancements and commercialization of laser scanning and sensing devices only enhance the possibility and availability of direct use of point clouds in digital twinning.

Implications regarding the updating process, thereby maintaining its actuality, point clouds are shown to allow for simple, yet effective change detection operations. Besides, a spatio-temporal approach is suggested to enhance actuality while allowing for access to ‘old’ representations. By doing so, point clouds offer the benefits of being a realistic, accurate representation while allowing for direct change detection and corresponding updates which is essential for a digital twin.

6. Future work & Recommendations

This research has shown that direct representation of point clouds have added value over common 3D modelling techniques when representing a digital twin. Moreover, clear limitations and shortcomings of current digital twin projects have been addressed. As the market for digital twins is expanding and increasing interest in 3D digital twin representations increases, directly using point clouds for this purpose provides a rather new, yet beneficial way of representing reality. Although this research did not develop nor design a digital twin as such, the contribution of this research is relevant in terms of describing the current way of digital twin development, addressing the limitations of these processes and provide the use of point cloud data in an accessible way.

Application

Nevertheless, the outcomes of this research are rather general in terms of their multi-applicability, as the focus has been primarily on exploring existing methods and developments regarding the direct use of point clouds as digital twin representation. Extending this research towards specific application fields will lead to new insights regarding the practical execution of the proposed framework. One of the application fields in which this research can be applied is the Architecture, Engineering and Construction (AEC) industry. As this industry is continuously innovating, digital representations are increasingly being used in design processes as well as actual construction and monitoring. Broadly implementing the use of digital twins within these processes will contribute to efficiency, while allowing for new insights.

The use of point clouds for construction progress monitoring is a topic of research that has recently gained increased attention. Tuttas et al. (2017) address the successful use of both handheld cameras and UAVs to generate point clouds of a construction site to monitor the state as-is in order to compare it to the as-planned BIM. Furthermore, research by Han & Golparvar-Fard (2017) addresses the use of 4D point clouds to visualize changes in time by using multiple point clouds captured at multiple points in time in order to monitor the construction progress.

Within the Architecture, Engineering and Construction (AEC) sector, LiDAR and photogrammetry techniques are increasingly being used in construction site monitoring, whereby frequent scans of the site are integrated in an already developed 4D model as addressed by Boje et al. (2020). The concept of 4D modelling, is not new and has already been applied in construction in which BIM and CAD are the most commonly used techniques. Point clouds are increasingly being used to update these BIM and CAD models. The use of point clouds for inspection regarding the state of real world objects as bridges can be seen in the examples provided in paragraph 2.2, showing the ‘Drieharingenbrug’ in Amsterdam and the ‘van Brienenoordbrug’ in Rotterdam.

Automation

Moreover, technological advancements will keep on pushing boundaries of what is possible, thereby continuing to increase efficiency regarding time and cost aspects of creating, updating and maintaining digital twins. This is only enhanced by the direct use of point clouds when being adopted as common way of representation. However, this research has only mildly addressed the developments regarding automation processes as being a topic that gas gained interest. Nevertheless, huge opportunities lie within automation, whereas in recent years, deep learning and artificial intelligence have gained massive attention within all sorts of application fields. These developments will only complement the developments regarding point cloud processing, digital twinning and change detection.

Sensing and measuring

Following the developments and innovations related smart city and IoT, the distribution of sensors and measuring equipment across cities is at an all-time high. At the same time, consumer electronics and vehicles are increasingly equipped with a variety of sensors as well. All these sensors collect data about the environment, both for instant feedback (e.g. parking sensors on cars) as well as long term monitoring (e.g. air pollution sensors). However, the possibilities for using this data are broader than the context they are used for. When car parking sensors and cameras can be used to detect obstacles, they can also be used for change detection purposes in the physical environment. Besides, point clouds have the potential to obtain the same status as contemporary photos and videos. Current high-end smart phones are already equipped with laser scanners to provide real-time 3D representations. The process for change detection and updating digital twins can highly benefit from these development if they extend towards the integration of laser scanners in lower budget smart phones or even low-budget consumer camera devices. This highly enhances the possibilities and ease of point cloud acquisition, whereby changes can be detected more specific and more frequent. Besides, suggested updates can be supplied by citizens, companies and government employees alike. Although all these developments have practical implications regarding data ownership and storage, future research can provide insights to which extent these technologies can contribute to keeping digital twin cities up to date.

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