MSc thesis in Computer Science

Real Time Interactive Collaborative Exploration of Urban Data with Virtual Reality

Mirko Dunnewind

2023

TU Delft

DELFT UNIVERSITY OF TECHNOLOGY

MASTERS THESIS

Real Time Interactive Collaborative Exploration of Urban Data with Virtual Reality

Author:
Mirko DUNNEWIND

Supervisor:
Prof. dr. ir. Alessandro BOZZON

A thesis submitted in fulfillment of the requirements for the degree of Master of Science

in the

Web Information Systems Group
Software Technology

June 26, 2023

Declaration of Authorship

I, Mirko DUNNEWIND, declare that this thesis titled, “Real Time Interactive Collaborative Exploration of Urban Data with Virtual Reality” and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed:

Date: June 26, 2023

Abstract

Immersive technologies, such as head-mounted devices for Virtual Reality (VR), have experienced increased availability on the consumer market. This opens up numerous possibilities for scientific research and industrial applications. But, configuring and combining data from various sources to create an effective visualization to explore, collaborate in and interact with, has only been researched in limited aspects. This thesis aims to demonstrate the feasibility of integrating these diverse aspects into a single application while preserving their individual potential.

To achieve this objective, an extensive analysis of the literature was done to establish the state of the art. All aspects necessary to create a single application were investigated to define how much of the literature fully or partly implemented them. Findings of the literature were summarized through definition, progress, limitations and improvements.

Based on the analysis, a proof of concept was designed and implemented, which established a virtual reality framework for real-time analysis and exploration of heterogeneous urban data. The framework involved the development of both a client and server applications with real-time communication. The server application processes and caches input data based on a structured configuration file, while the client application renders and visualizes points and shapes based on instructions from the server. The layered processing approach in this proof of concept facilitated real-time data handling and exploration. Which also makes it possible to collaborate with multiple people working on or manipulating the same data at the same time.

Evaluation of the server application showed its capability of processing over 1.000.000 objects from GeoJSON data. After initial rendering, the client application could update over 4.000 objects with a latency of just 200ms, which is considered to be interactive. Feedback from experts further supported the validation of the proof of concept application as a viable solution to the research question.

This research established the validity of a configurable real-time analysis and exploration solution in virtual reality. With further development and research, this tool holds potential for being used in diverse environments dealing with urban data.

Acknowledgements

This thesis was done at the Web Information Systems group of the TU Delft, to obtain my degree of Master of Science, in Computer Science. It has come together over the course of a few years due to several personal setbacks and the corona pandemic. Nevertheless, this report finishes that period.

I would like to thank my supervisor Prof. Alessandro Bozzon for all the help and trust he put in me. Even after the long trajectory, Alessandro kept providing supervision and a path to a finish. His support was always welcoming, and his feedback of excellent quality. Thank you for helping me finish this project.

I also would like to thank Wo Meijer from the Faculty of Industrial Design Engineering for his support with the evaluation in the last weeks and providing valuable feedback. He connected me with other people in his department, which I am also thankful to for helping me with testing the application. Additionally, I would also like to thank the VR Lab directors from the faculty of Architecture and the Built Environment for taking the time to talk to me, test the application, and provide useful feedback.

Last but not least, I would like to thank all the loving people in my life who supported me throughout the years and hard times. Especially to those who not only supported me, but also pushed and helped me bring my masters to a conclusion.

Mirko Dunnewind
Delft, The Netherlands
June 26, 2023

Author: Mirko Dunnewind
Student ID: 4097343

Thesis Committee:

Chair: Prof. dr. ir. Alessandro Bozzon, Faculty EEMCS, TUDelft
Committee Member: Prof. dr. Huijuan Wang, Faculty EEMCS, TUDelft
Committee Member: Prof. dr. Christoph Lofi, Faculty EEMCS, TUDelft

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Chapter 1

Introduction

Since immersive technologies like head mounted devices have become increasingly available on the consumer market, they are opening new possibilities for research. In 2015 new research became a rough starting point of Immersive Analytics [1] as a discipline. This new research direction was still scattered into different disciplines till 2018 when a whole book on the subject was introduced [2]. Both are defining definitions of Immersive Analytics and the various aspects related to it, like immersion, effective user interfaces, and interaction. For Urban Data, the concept of urban visual analytics has roughly been introduced in 2017 [3], creating another division in research. But most importantly it was questioned "how do we develop generic platforms that support immersive analytics?" [1], which will be further defined and answered in this work within the context of Urban Data.

Applying analytics and visualizations on urban data finds its origin within Geographic Information Systems (GIS), which do this to all kinds of geographical data. They combine virtual environments with abstract geolocation data for research. Also, GIS in general is becoming more focused on computer aided analysis where the user can directly control the parameters of their input data [4]. With the fast amount of newly collected urban data, data driven decision making is becoming more important. A platform which supports such decision making processes without having to bother about the technical aspects, is a must to allow wide access and adoption. This requires a multi-domain approach as many solutions are made for specific domains [5]. This research is based around urban data, which can be seen as a sub-section of a multi-domain approach.

With the availability of immersive technologies, the field of immersive analytics was created. In this, Virtual Reality (VR) plays an important role as the technology to reach a high level of immersion and as a potential research tool for all kind of studies [6]. Exploration and analysis done in VR is getting more common. To support these studies, there is a need for workflows in, amongst others, situated analytics [2]. These workflows are especially needed to support collaboration on which more research in immersive environments has to be done [1].

Combining all this, there is a need for a tool or platform [1]. This builds further on the concept of a data processing pipeline [7]. As VR is a whole different and especially new technology, there is a whole new set of requirements. This will be further described in this work.

The following non-numbered sub sections each describe a crucial part of the problem in more detail. **Urban data** refers to the data domain and thus what will be worked with. The **components** are the various parts which the system will be build from.

These are especially the parts which require research. Lastly, the **platform** is how all these parts will be brought together.

Urban data

The domain of geospatial data is broad. Geospatial itself is defined as any data which has a direct or indirect reference to a location on the earth. Generally, those locations are represented in GPS coordinates. For this research the focus lies on exploring **Urban Data**. This is any data which is tied to assets or activities within cities. Amongst others, this data is generally used for decision making [8], urban planning [5], public services [9] or traffic flow [10]. As will be later introduced, the exploration shall happen in **Virtual Reality** to make use of its immersive features. For the usefulness of immersion in the visualizations, when talking about urban data, only urban data with geospatial properties are meant.

The components named below are derived from the nature of urban data in the modern world. There is a fast amount of heterogeneous data growing in a real time manner. Where exploration, interaction and collaboration are key in analysing, interpretation and presenting such data. In which a realistic view in a virtual reality environment stays more true to the source of the data to help the interpretation processes.

Components

Building such a tool for the urban data domain is especially interesting and useful when combined with various other aspects. The aspects which are considered are listed below. The choice for these comes from the context and goal for this thesis as well as literature suggesting their use. This work can be seen as a combination of 5 components of previous work combined with urban data.

- **Exploration**: Being able to explore data is a necessity for a good research process. Providing the tools to efficiently not just navigate the data, but also customize the data representation and visualizations, is important for a good understanding [2], [8], [11].
- **Virtual reality**: Due to the nature of urban data being close to reality, virtual reality (VR) is a beneficial aspect when working with such data. The immersive capabilities of VR can help in understanding [12]–[14] and is a potential research tool for all kind of studies [6].
- **Interactive**: Being able to explore the data in a self configured format, is not reaching its full potential if there is no direct interaction possible. Especially when considered with virtual reality, the immersion should not be broken, which is necessary to tie exploration and virtual reality together.
- **Real time**: Urban data research is by nature very timely and a lot of the data sources from live streams. To view, edit and/or annotate such data in real time can be crucial for making efficient use of such a tool [8], [15], [16].
- **Collaborative**: With collaboration multiple researchers or users can combine their knowledge and insights about a certain data set and domain. Research suggests that collaboration is very useful in research and positively impacts the discovery, sense making and decision making process [17], [18].

Platform

In many research the urban visualizations are build just to test hypothesis unrelated to building the visualization itself [15], [19]–[22]. They are putting a lot of effort in creating the platform for their domain specific research. There is a need for a more generic tool which can support a more broad domain [5], [15]. Some are already working on such tools [10] and are providing valuable insights in the needs and problems of such a configurable platform.

Various tools were already building towards a multi-purpose application [9], but they did not manage to combine all components. A more configurable approach is needed to make visualization more cost effective [23] and available to more users in more situations. Just like how some wish for such an urban visualization tool with real-time data fetching capabilities [15].

Combining all these components into one platform, while staying true to its potential, is the challenging part. The unique features of each component must all work together in a configurable way. This will create a multi-purpose platform which can be used by researchers and other users for their own goals without having to spend unnecessary resources.

1.1 Example use cases

To give an impression about what a platform like this could do, two examples are presented. More example use cases will be presented in the Example usage section at the end of the System Implementation chapter.

A platform like this could help with TU Delft campus research. There is a lot of data available from all kinds of sources around the campus. Being able to visualize them on top of a map, perhaps with 3D buildings, could benefit exploration. Especially in the earlier phases of analysing the data, such a platform would help going through the data, finding research directions, and explore in collaboration with others. Additionally, various data sources around the campus are also updated frequently and could be a good source for presenting real-time data on the platform.

It is not uncommon that research collects annotated data through employing users. This platform could help if having a virtual reality environment would benefit the research or annotation collection. Visualization and exploration can provide a better representation of data and reality, which could improve annotation. An added bonus would be doing it in collaboration. Within this example, the annotated data could be reached by implementing it as real-time data.

1.2 Challenges

The introduced problem and combination of components poses various challenges. These challenges will be overcome by research and deriving requirements for a system to solve the problem. As was introduced before, there is a need for a framework capable of visualizing and exploring heterogeneous urban data. For this, the following aspects are believed to be important to research.

1. **Exploration** requires a way to customize and visualize any supported data. The challenge is incorporating this into the whole processing pipeline, while not limiting options and affecting the performance.

2. Using **virtual reality** to view urban data is a very logical choice and has a lot of benefits. However to make full use of all the benefits, the data visualizations should be merged within the environment while keeping the immersion at all time.

3. Exploration is nothing when there are no **interactive** options. To interact with the system and data while being in the virtual reality environment, it is important to not break the immersion. For a system which requires explorative actions, this is challenging.

4. Supporting **real time data** is important in the context of the urban data. Doing this in a configurable way to support exploration is challenging as it requires all parts of the system to account for this.

5. To improve scientific research with the data, **collaborative** functionalities are a must. Together with the above challenges, this is the most challenging as it has to combine everything in a real time and performing manner. On top of that, it requires additional tools to make the collaboration effective. Within this work collaboration is seen as multiple people working together with the same data at the same time.

6. **Urban Data** comes in a wide variety of forms and just as much use cases. To support this heterogeneous data, as much use cases as possible should be accounted for, and not be restricted to one type of domain.

7. When combining all the **components** the system should stay true to the potential of every component. Doing this for all components at the same time is a challenge.

These challenges, amongst others, are the basis for the investigation of Related work. From both the system requirements will be derived and introduced in the System Design chapter.

1.3 Research question

Within this thesis and the provided context in this introduction, the research question below is central. It is split into 4 different research sub questions which will all attempt to answer a part of the main research question. The answers combined should be able to accomplish the goal of this thesis.

RQ How to create a Virtual Reality framework for real-time analysis and exploration of heterogeneous urban data?

- **RQ.Sub1** What is the state of the art of configurable applications for visualizing heterogeneous urban data?
- **RQ.Sub2** How to design such a framework while accounting for configurable non-defined use-cases?
- **RQ.Sub3** How to build such a framework while keeping it performing with live data and usable for interactive collaborative research?
- **RQ.Sub4** Is the proof of concept framework usable while solving the problems at the same time?

Each chapter will answer one of these sub questions and respectively match a contribution as will be discussed in the next section.

1.4 Contributions

Following the research sub questions, the following contributions will be made. Each of the following chapters will be providing one of these contributions.

C1 - State of the art review A complete review and analysis of the state of the art.

C2 - System design The design of an application which supports the given requirements.

C3 - Prototype system implementation An implementation of the proposed design which will serve as a prototype.

C4 - Evaluation by experts and performance Evaluation of the prototype system by expert users in regards to the state of the art, as well as a quantitative evaluation to measure performance.

1.5 Thesis structure

To demonstrate the validity of this introduction and project, the next chapter will present all the related work in a structured manner. This will substantiate the claims made in a concrete way. Chapter 2. Related work will go into detail on the methodology used, the urban data domain and the state of the art about the various components.

In chapter 3. System Design a system will be proposed which suits the needs of the presented problem. After that in chapter 4. System Implementation the actual implementation will be described. This is followed by an evaluation of the created system in chapter 5. Evaluation. At last this thesis is closed by a conclusion in chapter 6. Conclusions, which also presents suggestions for future work.

Chapter 2

Related work

In this chapter the literature related to the problem, as introduced in introduction, is discussed and evaluated. Firstly, the methodology of navigating the relevant literature is described. In the State of the art section the literature itself will be evaluated and discussed through multiple components. Lastly, some conclusions will be drawn.

The components which will be researched are the aspects which are deemed the core of a true urban data platform. Derived from the characteristics of urban data, these components are needed to get the most out of the fast growing collection of heterogeneous data. Exploration is especially needed to be able to easily look at more data. Interaction and collaboration is a necessity for research and the sense making process of the data. Lastly, virtual reality and real time are characteristics of the urban data source, which provide a more natural representation as well as being able to view new data without a delay. Accounting for all these aspects together, will form the proposed platform.

2.1 Methodology

This section describes how the literature was retrieved. In order to define if this thesis is relevant and novel, it is important to adequately know other research surrounding these topics. With this applied methodology the work is positioned to the best of my knowledge. Guidelines for systematic literature reviews[1] were used to help define the methodology.

Based on the context and goal, the first literature was found through Google Scholar. As the area of immersive analytics and consumer grade head mounted devices is relatively new, most searches were restricted to show results of a maximum of 5 years old. Different search cycles were done in order to build upon newly acquired knowledge. Each cycle consisted of picking literature (based on the first impression) from the first 50 results in Google Scholar for a given set of keywords. The resulting literature was evaluated and compared to the thesis goal. With the acquired information, the next search cycle was initiated.

After reading the literature and extracting information useful to this thesis, a structured document was build to keep track of the collected information. From this literature, a set of common keywords was compiled and used for an additional search.

[1] S. Keele *et al.*, "Guidelines for performing systematic literature reviews in software engineering", Technical report, Ver. 2.3 EBSE Technical Report. EBSE, Tech. Rep., 2007.

Also, references from the literature which looked promising were added to a list to feed the last search cycle. This whole research flow is visualized in figure 2.1.

For the literature found and deemed relevant, qualitative and quantitative categorizations were made to better understand and find relations. Amongst others, it was defined how much each work relates to the components of this thesis as defined in the introduction. Looking more thoroughly into those dimensions, will give a better understanding about the research gap. Based on these categorizations and metrics, literature was picked to be relevant or not. Relevant literature at least should have some relation to one of the components as well as be able to give insights in the introduced goal and challenges.

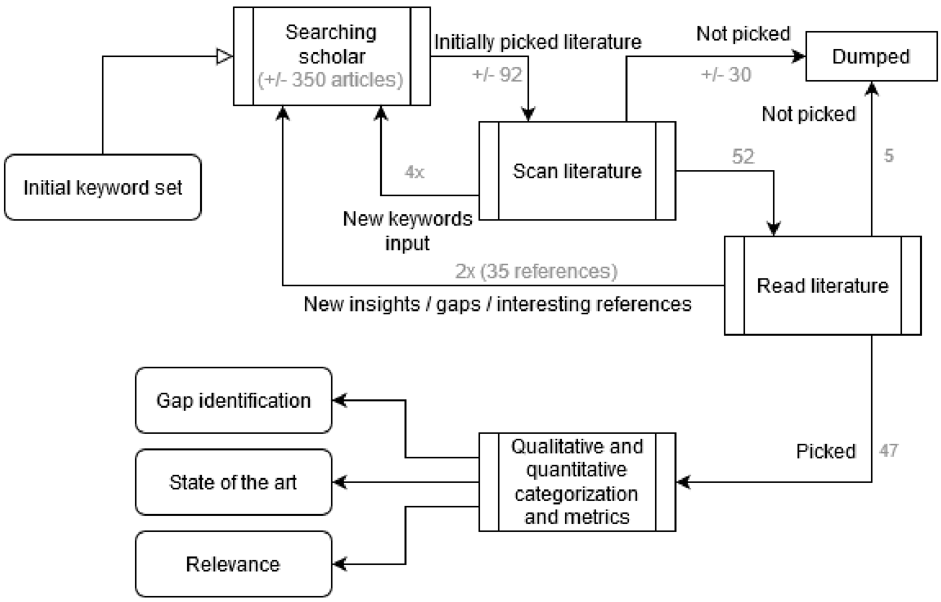


FIGURE 2.1: Flow of the methodology used to research the state of the art. The single numbers describe the total amount of literature flowing in the given direction. Reverse lines with a number and times symbol describe how much times the action was done.

2.2 State of the art

In this section the state of the art will be investigated through different aspects which are referred to as the **components**: 1) Urban Data 2) Exploration 3) Virtual Reality 4) Interactive 5) Collaborative 6) Real Time. For each of these, it will be looked at how it is **defined**, what **progress** was made, current **limitations** and what **improvements** should be done as a next step.

Table 2.1 shows various literature works, retrieved through the earlier described methodology, and to which component(s) they belong. Some only *partly* implement or research the topic and are thus mentioned as such. Those which are combining multiple components are marked bold and will be more extensively looked at as they are most likely closer to the goal of this thesis.

Various GIS (Geographic Information System) and VGE (Virtual Geographic Environments) implementations provide a broad set of features already. However they are mostly constructed for 2D environments and geographic large scale processes,

TABLE 2.1: Literature which includes information about a component. Those containing multiple components and are especially interesting, are marked bold. The "Yes" column defines the literature which focus or implement the component, while the "Partly" column only does this partly, yet provide useful and relevant insights.

	Yes, focus or implementation	Only partly
Urban Data	**[25]**, **[26]**, [27], [28], [9], [8], **[5]**, [2], [19], [23], [15], [3], [10], [21], [29], [30], **[31]**	[32], [33], [22], [20], [34]
Exploration	[32], **[25]**, [16], **[26]**, **[7]**, **[5]**, **[31]**, [29], [35], [36], [37]	[38], **[39]**, [10], [40], [41]
Virtual Reality	[42], [14], [32], [43], [22], [28], [44], [17], **[5]**, [10]	[38], [1], **[26]**, [27], **[7]**, [19], [15], [20], [21], [45]
Interactive	[14], [32], [38], **[25]**, [16], [22], [44], **[39]**, **[7]**, **[5]**, [10], [35], [37]	[46], [33], **[26]**, [12], [30], **[31]**, [40], [36]
Real Time	**[25]**, [16], **[31]**	**[26]**, [9], **[39]**, **[7]**, [8], **[5]**, [2], [18], [40], [13]
Collaborative	[33], [43], **[25]**, [47], **[39]**, [2], [18], [12], [40], **[31]**, [45]	[14], [8], [41], [48], [49]

like weather. Even though for those conceptual systems and environments, tools exist, they are still in need of better and more generic tools [4]. VGE's focus more on the virtual environment, however that is only one of the important environments to consider [50]. It is also important to look at the data-, collaborative- and interactive-environments. For the combination of components as provided in this work, to the best of my knowledge, there exists no suitable system, nor framework which takes the important aspects of all components into account.

All these components are important as will be discussed in the next sub-sections. The need for this combination emerges from the nature of urban data and how it becomes larger and more complex every day. There is a need to make quick sense of heterogeneous data in dynamically defined environments which can adapt to changes and specific cases [11]. Available applications are specific and domain based [49], while the data grows without tools to provide a quick setup for viewing and analysing. For standardisation and the adoption of the combination of these components, a tool is needed.

2.2.1 Urban Data

DEFINITION As already defined in the Introduction, Urban Data is any data which is tied to assets or activities within cities. For the purpose of this work, such data is limited to data with geospatial properties which are suitable for immersive virtual environments. Within Urban Data, 360 degrees images like Google Street view are also considered as they have a geospatial location and posses immersive properties. Example usages of geospatial data are amongst others: Twitter data [32], geological soil information [44], weather data and models [41], public services data like bus stops [9], or Google Street view images [26].

PROGRESS Recent research has focused extensively on enriching a map with additional data. This can be the location of twitter posts [31], adding 3D buildings for sound reflection models [15] or showing public service data in combination with 360 degrees images [9]. Other research has not focused on maps, but other aspects like urban planning, neighbourhood/park safety, representative visualizations, etc.

The urban data aspect is mostly used in research to test out various user reactions and interpretations by attempting to represent the real world as well as visualize data to create a better understanding. Additionally, they are researching how data can be visualized in a virtual world for analytical purposes. In [3] they describe this last focus as "urban data analytics", which became a field around 2017.

One implementation tried to visualize a university campus through various aspects [29]. While still manually combined, they did make a proof of concept on how maps, terrain height, building shapes and detailed building models could be combined in the same visualization. Other work did roughly the same but with urban city data which was visualized as an abstract heat map layer on top of a map with building shapes [10]. Another example builds towards showing a city through 360 degrees images from a map view [21]. These are all examples of research which can act as building blocks for a toolkit.

LIMITATIONS Most research limits itself to only one source (not combining) or combining only two sources. Implementations like [10], [29] combine more data sources but are very limited in how dynamic they are. They require an extensive amount of manual steps to produce the visualizations as will be discussed more in section Exploration.

Another essential limitations which will also later be discussed in the Exploration section, is the data format. Within various industries different data standards are used. Which, if they even exist, are mostly non-official standards. This makes it hard to work with Urban Data especially if sources have to be combined. What can be seen is that more traditional GIS systems as well as much government provided open data are working with shapefiles, this while online digital map tools mainly accept GeoJSON as their standard. These are the only two standards which occasionally are used and should both be taken into account.

IMPROVEMENTS There is not much research that highlights what they need in term of tools as they generally have a goal not purely related to Urban Data. Most do wish to have had better tools so they could focus more on their actual goal. From this it can be deduced that the data needs to be more standardized for more tools to be build and adapt it. By supporting common input formats this can be improved.

A good base system is needed, for which mostly a map has been used. The map can be combined with various kinds of data [5], [26]. This would be a good starting point for the framework as a map possesses the properties of urban data and has the benefits of being a known tool to users as well as give a good way to orientate in the virtual world.

2.2.2 Exploration

DEFINITION To explore data, the user does not only need to be able to navigate the data, but also customize their data and visualizations. In the context of exploration, being able to navigate the data is taken for granted as this is a basic need for most types of application. The ability to customize the data input, use multiple sources and combine this into visualizations is needed to explore. Thus to support exploration, it means having customization.

	Yes	Partly
Custom data	**[38]**, **[25]**, **[16]**, **[9]**, **[17]**, **[39]**, **[7]**, **[5]**, **[40]**, **[31]**, [13], **[35]**, **[36]**, **[37]**	[14], **[26]**, [44], [10], [29]
Different sources	[32], **[38]**, **[25]**, **[16]**, **[26]**, [22], [28], [44], **[9]**, **[17]**, **[7]**, **[5]**, [23], [15], [10], [29], **[40]**, [30], **[31]**, [41], **[35]**, **[36]**, **[37]**	[39], [13]

TABLE 2.2: Literature which include some form of exploration. Split in literature which is using custom data, and those which allow different sources. References which are trying to do both, are made bold.

PROGRESS About 25% of the reviewed literature had some sort of option to customize their data. For example [7], which allows the user to configure the visualization through a structured configuration file. However, most of these custom data implementations do require some form of manual processing. In [25] the data is only manually pre-processed and loaded, while others like [23], [28], [29] even require manual processing and actions up to the visualization step. Even though they require manual steps, they refer to it as their systems being able to work with any input data. To truly accept any custom data, the system should work automatically from the point any supported data is entering the system. This excludes the minimum manual steps of a basic configuration required to process the data and define the visualizations to fit the research goal of the user.

The first step in exploration is the input data itself. Research like [10] acknowledge there are no uniform data standards and others are attempting to solve this by accepting more types of data like [26]. To accept at least the most standard types of data, the next step is having good pre-processing. This is especially needed when combining data as [41] suggests.

By having those both aspects in place, the application will be in control of the data and can align the whole processing into creating supported visualizations. For this to work a clear categorization is needed [41] to map data to suitable visualizations. The work of [5] goes a bit further in this step and combines different sources by using "visualization primitives" which are configurable and thus support different types of data.

Combining various sources in a configurable way, is mostly not done yet [16]. They sometimes do combine some sources, but with limited capabilities such as being static, nonexchangeable or no virtual reality. Research has been building towards applications which accepts more kinds of data [26] and presented various use cases for their application. Others presented workflow to go from data to an integrated virtual urban environment [10]. Table 2.2 shows quite some literature trying to do both, however all these application lack some form of configurable capabilities and are more theory than implementation.

LIMITATIONS Most of the literature limits their data processing to their specific research goal. Which means only their specific data source and goal can be explored. Those who have slightly different questions, are not able to use the same methods without building a part of the system again. So, the main limitation is not being able to customize the current systems.

The researched methods and applications are not taking Virtual Reality or Collaboration into account. They are very limited to their chosen way of visualizing and their single purpose goal of the application.

IMPROVEMENTS A more generic approach is required to create a toolkit which support various research goals. For this to work, a flexible processing structure has to be created, which can handle various types of formats and is able to prepare different kind of visualizations. One of the big challenges here would be keeping performance good enough for partly real time editing, which will be discussed in the Real Time section.

As a major part of improving the exploration of data and thus customizing the processing and visualization, a configuration is required. This is a very specific part of exploration and will be elaborated upon in the next sub section.

Configuration

A big aspect of exploration is configuration. Users of the system should be able to configure the platform to be able to work with their own data and research goals. Some tools like [7] are already implementing highly configurable approaches. In terms of configuring general analytic visualizations, quite some research has been done in high level configuration languages. Vega-lite [35] and Reactive Vega [36] are examples of such efforts and will be used as inspiration to build an immersive urban visualization variant.

The process of configuration should be easy to understand so more researchers can make use of the system. This can be done by implementing step-by-step configuration like [25]. Their configuration allows the user to link data fields to visualization properties when adding a new component. It should also be easy to configure new data and support various ways of inputting data like [7].

Lastly, it is beneficial for the configuration to be saved in a structured file as is done in [7], [35], [36]. This allows for, amongst others, more configuration options to be added without having to build a user interface for all the niche configurations. Just like [7], the processing pipeline will use the configuration to control its behavior. To support dynamic data and configuration updates, which will later be needed in the Real Time section, the processing structure should be build with this in mind like done in [36].

2.2.3 Virtual Reality

DEFINITION Virtual Reality (VR) can be seen as mirroring the real world. All technologies have in common that they create some form of immersion. This can be in various degrees, like a singular big screen has low immersion, CAVEs[2] have already quite some more immersion. At the moment the most immersion can be reached with a stereoscopic view by Head Mounted Devices (HMDs). The level of immersion also depends on how one can interact with the system, how realistic the virtual environment is, and if the system follows the view of the user. For example, in CAVE systems one user is sometimes followed, to which the environment is tailored. Because in this work VR is combined with Urban Data, only HMDs are considered as

[2] A cave automatic virtual environment, where a virtual environment is projected on walls, rendered from the perspective of one tracked user in the physical room

they are the most immersive technology and are more available due to the technology reaching the consumer market.

Immersion is a very important concept as it is the aspect of VR which especially creates the benefits [12]. Immersion can even differ a lot within the same system. To make full use of all the benefits, the level of immersion should be maintained as much as possible while the system is being used.

PROGRESS Within a lot of domains this has been researched. In the earlier stages this was mostly done with CAVE systems. Since head mounted devices with stereoscopic view have recently entered the consumer market, and are becoming increasingly better, the research has been shifted. For urban data it has been found useful for many reasons. Virtual reality and thus HMDs can help studies in other domains effectively [20], even if the tool is relatively basic.

In general, VR has been found to be useful as a potential research tool for all kind of studies [6] or different scenarios [17]. It also increases the interactivity with the data [45] and functionalities like switching views can attribute to learning. Thus, the immersive factor of VR plays an important role.

For an urban data use case it has been found that VR promotes the knowledge discovery process [5], which is beneficial for the exploration focus of this work. Other research also showed that it is possible to interactively combine VR with lots of data in an urban environment [10]. Immersive high level views of a map providing relevant information and time temporal data was also found to be helpful to come to new insights [22]. This proofs the usefulness of a combination of various visualizations in VR.

LIMITATIONS Of all components, this aspect has probably been researched the most. However there are some limitations when combined with Urban Data and Exploration. Most applications are tailored to very specific use cases and above all, it is not much used for exploration of urban data, just for viewing. Which means it is missing the ability to configure the system as well as keeping the immersion throughout the whole usage.

IMPROVEMENTS Next step would be to make this a critical part of the application and exploit its benefits. On virtual reality itself, not much has to be improved or researched, it mainly has to be tailored to work efficiently with all the other aspects and maintain immersion.

2.2.4 Interactive

DEFINITION As opposed to exploration of the data (navigation and freely defining data), interaction in this context is defined as the user being able to interact with the visualizations in the immersive environment. This can range from viewing details of a single instance, to operations like filtering, brushing or navigation.

Information and means of operations should be directly embedded in the virtual world in such a way that it appears to be a part of it. This is needed to avoid losing immersions [30], which was defined as important in the Virtual Reality section.

PROGRESS Interaction is generally used as a way of controlling the visualization or information flow to the user, but its effects on the immersion and user experience are not accounted for. Tools like [5] add quite an extensive set of interactions to a map with (partly customized) urban data, however all their interaction is placed in overlays or in other windows and not immersed.

Most implementations have created very specific interactions for their application goals. While they are limited, they are good examples of how interaction can be implemented. Within the VR world created by [22] it is possible to interact with various components to get more information or highlight their time temporal relation with other components. The implementation of [10] goes a bit further and allows interaction with different kinds of data with amongst others selecting and layering. However, their examples show only an indication on how it would look with immersive interactions, while others show non-immersed versions.

Apart from how the interaction is presented, it is also important to support a standard set of data interactions out of the box. While not immersive, various tools like [5], [7] allow interactions like brushing, linking, grouping and filtering in a generic way.

LIMITATIONS In regards to the combinations of these components, not much has been done in depth. Most is limited to either simple immersive windows or a bit more extensive interaction out of the immersive environment.

As with most of the components, also this aspect has mostly been implemented for specific goals with very specific data and visualizations. It is limited in the way that no exploration, the most important aspect, is hardly possible. The data interactions themselves are thus not implemented in a very generic way to allow them to be applied on more kinds of data.

IMPROVEMENTS When working with virtual reality, interaction should be supported out of the box by the toolkit. Especially immersion should be taken into account and allow for most interactions to take place directly in the virtual world. It should be looked into how this can be better implemented without breaking the immersive experience.

Besides the immersion and thus how the interaction is presented, a set of standard data interactions should be made possible. It should be looked at how they can be implemented in the framework in such a way that it is easy to extend or add more.

2.2.5 Real Time

DEFINITION Within this context, real time can have two distinct definitions: 1) The data is being updated in a real time manner, thus receiving updates within small frequent time intervals. 2) The data can be updated or added upon in a real time manner, thus creating new information while using the application. A common example of this last definition is data annotation. Especially in combination with collaboration this can pose opportunities as it can make working together easier. Implementing this in the application data processing pipeline will also make the system able to easily adapt a strategy for showing the position and actions of other collaborators in the virtual world.

PROGRESS Only a handful of literature has studied this within the context of urban data. Those who studied it, generally mention it as a part of their bigger system and end up not going into detail. Annotations are more common, but very use case limited. The use cases for annotations in virtual reality is mostly focused on researching input devices, but not on managing the data. The use of specific and manually created data sets is very common on this case.

The implementation of for example [31] fetches additional information on demand. In this case it is about Twitter data for a single tweet or location. This feature could be seen as a form of real time data as it updated the data, but with an internal trigger. Their implementation possibly also streams data from Twitter as input source, but that is not further discussed.

The research of [36] uses a configuration and processing structure which can account for real time data and only update the relevant parts to keep a good performance. This still requires quite some configuration and is not build for urban data, but is a good basis. Other tools do build around urban data [25] and allow some basic sources to be directly added within their application. They build towards a more generic implementation of dynamic data sources.

LIMITATIONS Especially in regards to real time updating of the data, there are limits. In most cases the processing is very much tailored to exactly the data the literature is studying, in such a way that real time updating only works (or is researched) for that specific data. Annotations can also be seen as a form of real time updating, but is mostly not a part of the data processing pipeline. This limits how annotations can efficiently be reflected to an other user in case of collaboration. In order to support both distinct real time data cases, the data processing pipeline should account for this.

IMPROVEMENTS Real time updating is not much researched and will probably encounter various problems in terms of performance and exploration/customizing when implemented. The first step towards this is accounting for real time data input in the processing pipeline. This means annotations should be a part of the input data and the pipeline should be able to selectively process and visualize only the updated data.

In particular data should be able to be fetched from an external source in real time. There are needs for tools which can do this in the context of visualization of urban data [15].

2.2.6 Collaborative

DEFINITION Collaboration can be considered as working together on the same situation and problem to come to a mutual understanding, in this case the same data and environment. There are a lot of situations in which collaboration can have a positive impact on the discovery and decision process [18]. Especially in the sense making process when analysing data, it has shown great improvements in the results. But collaboration is also an aspect needed in for example learning environments or when presenting data findings. Within immersive analytics there is thus a need for collaboration [2], [18].

Collaboration can be split in two different ways [49], namely: co-located and distributed; asynchronous and synchronous. As the domain of this thesis lies in the immersive virtual world, the focus is on distributed collaboration as there are no physical objects which have a shared use. However co-located is not fully disregarded as voice communication does not necessarily have to be done through the virtual world. Furthermore, the focus lies on synchronous collaboration. Though asynchronous is possible in case of annotations, but this can be seen as a side effect.

PROGRESS In general a lot of research has been done on collaboration with digital data. The field of Computer-Supported Cooperative Work (CSCW) showed team work is important [40]. Collaboration is important in the sense-making process when exploring data [49] and to share experiences [44]. Visualizations are important in scientific communication [41] and in need of good collaboration. Being able to work together with the same data and same visualizations are thus important to facilitate discussions about the data [23] and implies collaboration is a necessity in data exploration tools.

Other research has identified various factors needed to support effective collaboration and discussed different forms of collaboration [48]. Visual cues about the other collaborators is especially important, for example knowing where the others are through avatars [31]. This however has only been tested in custom build applications and is generally plagued by synchronisation problems.

LIMITATIONS Most research is limited to testing how useful collaboration in itself is. For example [43] showed that analysing network connectivity was more accurate and faster in a collaborative VR environment (as opposed to a CAVE), so only showing that collaboration has benefits under certain circumstances. No one has done an effort to combine all the findings into an multi-purpose application and thus provide users with collaboration options without having to a domain specific solution [40]. As [49] states, there is a need for a tool which allows for a collaborative environment to be setup quickly, on order for it to be widely adopted.

IMPROVEMENTS The bigger picture is missing here and findings of other works should be combined into a set of important features to implement. Taking collaboration into account within the whole framework is a first step in the right direction. When combining this with the need for real-time data updates, it probably overlaps in features needed for it to work. A basic collaboration framework should be put into the tool to at least allow all collaborators to the see same data, as well as see what others are looking at.

2.3 Conclusions

It is clear that research is not really accounting for all the aspects together to utilize the full potential. Most applications were made with very concrete research goals in mind or required quite an extensive amount of manual data processing. For this, a single unified application which takes all component characteristics into account is missing. A clear need for a tool which can deal with heterogeneous data in a configurable way was expressed.

Various literature formed part of the inspiration to this work. The core of the information and inspiration in this work came from literature like [1], [25], [26], [38]. In addition to that, some literature did built likewise applications, with some overlap to this work, like [5], [7], [32]. As opposed to other research, this work will be different as it will not use a more specific domain than urban data. The technology in terms of hardware is set to head mounted devices. The application will be build with functionalities for general immersive analysis of heterogeneous urban data, which is the main difference this work is trying to make. A platform supporting such requirements will close the identified gap.

Current work has various limitations, both within the specific components and with combinations of components. Urban data is getting increasingly more volume, as well as more real time, making this work timely. This also makes the work relevant, especially together with virtual reality becoming more available. Data will have to be researched, making a platform to do this out of the box necessary and thus useful. To the best of my knowledge, there is no other research trying to combine all these components in one application, making this work novel. The core of what has been identified as limitations and thus what still has to be done, is the following:

1. Explore any supported heterogeneous data by configuration and no manual processing. Which will open up research possibilities to more users.
2. Accounting for VR characteristics when implementing the other functionalities to provide an effective virtual experience. This mostly has to do with immersion and keeping the immersion.
3. Adding out of the box interactivity, with the world and data, within the immersive virtual application.
4. Allow for real time data processing to support the nature of constant flow of urban data.
5. Implement the basics for collaboration to support sense- and decision-making processes.

The challenges from the introduction have now been further identified. To put these into practise, the next chapter will propose a design based on the derived requirements. The rest of this work will build towards solving these challenges.

Chapter 3

System Design

This chapter will describe the design of the system and shall elaborate on the choices. Most of the design decisions are derived from the related work in a direct or indirect way. Others are implicated from the problem description and motivation. They are brought together to form the theoretical application through models and other designs.

The rest of this chapter will first discuss user stories and is followed by requirements. After that, the general architecture will be described, which is enlightened in more detail in the models section. Lastly, a user interface design is provided. The chapter will be finished with a short summary and conclusion.

3.1 User stories

User stories describe how the application is intended to be used and what users wish to reach by using the application. These are all derived based on the related work, provided examples and problems this thesis presumes.

1. As a *urban data researcher* I want to **view my urban data**, so that *I can quickly draw preliminary conclusions*.

   Quick access to data visualizations can help researchers to check their hypothesises and pick a direction. It would be a waste of time to manually build every visualization.

2. As a *researcher* I want to **look at the same urban data with multiple researchers at the same time**, so that *we can work together to solve a problem*.

   Solving problems is proven to be more effective when done together. Being able to look at the same data in the same way is essential to convey a point of view when working together. Having this option available will improve the output of the researcher.

3. As a *researcher* I want to **configure the application freely**, so that *I can visualize the data the way I want*.

   The researchers want a parametric tool to visualize their urban data. This allows them to configure a visualization of their data exactly how they desire without building a whole application around it.

4. As a *researcher* I want to **freely navigate in the virtual world**, so that *I can look at and inspect the urban data from the perspective I want*.

A part of researching means that you will have to look at the subject in various ways in order to discover new information. It is thus important that a researcher can freely navigate around the data so no important viewpoint or perspective is missed.

5. As a *urban data researcher* I want to **view the data in VR**, so that *I get a better visual understanding of the data*.

   Representing data in a more natural way, especially in case of spatial data, can help understanding it. Virtual Reality has shown to be a useful medium for visualizing such data to improve the understanding and perception.

3.2 Requirements

The second step in the design process are the requirements. They are derived from the related work, user stories, and the problem description. Each requirement is written as a short description and is categorized. The categories of the requirements vary from being functional, data related, user interface related or technical. If a requirement is derived from the related work, the relevant part is referenced.

3.2.1 Functional

The overall requirements of the application. These are required for the application to function within the working scopes defined earlier in this document.

1. Ability to process GeoJSON, ShapeFiles and CityJSON input data.
2. Ability to present processed geo located data in a virtual environment, either by shapes, objects or data points.
3. Ability to visualize the presented data based on properties from the input data.
4. Ability to filter[1] the input data based on its properties.
5. Ability to map data objects to locations on a map.
6. Ability to explore the data in a Virtual Reality environment.
7. Concurrent clients operating on the same data sets, required to support effective collaboration.
8. Latency of maximum 200ms on user triggered actions in the virtual world. This is the widely accepted maximum latency to make an application feel responsive.
9. Manage the settings of the application through a JSON file to allow for full configuration options.

3.2.2 Data

More specific (input) data related requirements. These define in what scope of data the application can be used. Supporting this is believed to make the application useful for the problem description of this thesis.

[1]This refers to a user controlled selection of data in the final stage of processing, generally based on criteria applied on the properties of a list of items.

1. Accept files and URLs, which are one of the types of functional requirement 1, as data source.
2. Accept the data sources mentioned in point 1 to be able to periodically refresh, either through pulling or pushing the data.
3. Accept commonly used coordinate systems (WGS 84 aka GPS, EPSG:7415 aka RD NEW used in Dutch maps) and transform points between those systems.
4. Allow data to have meta data with additional information which can be used to view and visualize.

3.2.3 User interface

Specific requirements to the user interface are mainly necessary to improve the user experience and immersion. They do not necessarily block the usage of the application, but are important nevertheless.

1. View object related meta data in the virtual environment.
2. Adjust filters and visualizations in the virtual environment.
3. Easy to use additional interface for managing the basic configurations.

3.2.4 Technical

Various technical requirements which do not fit the other sections.

1. Developed in Unity for effective VR support.

3.3 Application architecture

The application is designed with a server and client structure. This architecture is necessary to support multiple users and thus collaboration. Having one authority to control the data also makes the processing and controlling of the source data easier as opposed to other network structures like peer-to-peer. The server is a single headless application which can be controlled through a network connection. In this design some inspirations were taken from [36] and other discoveries from the related work.

The client is there to visualize the data provided by the server. As the client is displaying a virtual environment which is supposed to be viewed in VR, all controls also have to be in the virtual world to avoid breaking immersion as much as possible. The basic configuration of the server would require the user to input data and define the visualization methods, which would be a rather complex task when emerged in a visual world. A web application manager client is to be made for general server control.

Figure 3.1 shows the global architecture of this suggested application. The internal component will be described in more detail later in this section.

Since this setup requires the configuration to be changed in multiple ways, the server should implement a configuration file based approach. Any controls from the client will change the configuration file, which in turn will selectively re-process data and

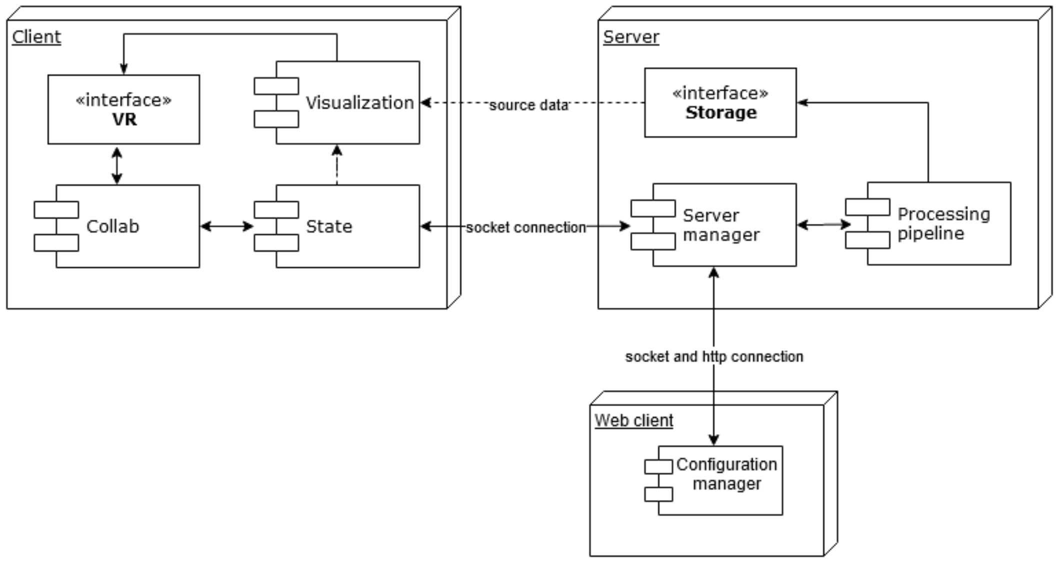


FIGURE 3.1: Global architecture of the application, showing how the various lines of communication and processes connect.

visualizations. With this approach it is possible to make a predictable way of processing all the data as there is only one source of truth. Additionally this means it is easy to swap or load configuration files when necessary.

Communication between the server and the clients should happen through live socket connections to communicate state changes and basic application controls. More precise configuration and uploading data files is to be done through a simple REST API. Lastly, the data files necessary for visualization are to be downloaded by the visualization client through the REST API. Dividing the data flow in this way allows the visualization application to selectively load data files only when a state change or the server notifies the client about a specific part which was updated.

A more detailed design and relation between the various components is displayed in figure 3.2. These components all have their own specific task and are added with a reason. In the list below each will be described in more detail.

- **Server**
  - **Server manager** - The server core which manages all the connections and processes. It controls the processing of the data, owns the configuration, manages the clients and makes sure all state changes are correctly forwarded to all clients.
  - **Config** - The configuration which the server is running.
  - **State management** - Holds the state of the various components and processing steps. This makes sure there is a straight forward way for every component to know which state the application is in.
  - **Processing** - The main processing. It controls and directs pipelines based on the application configuration passed by the server manager for a single run.
  - **Pipeline** - Tasked with processing a small and specific part of the configuration. These are processed after each other as each pipeline depends

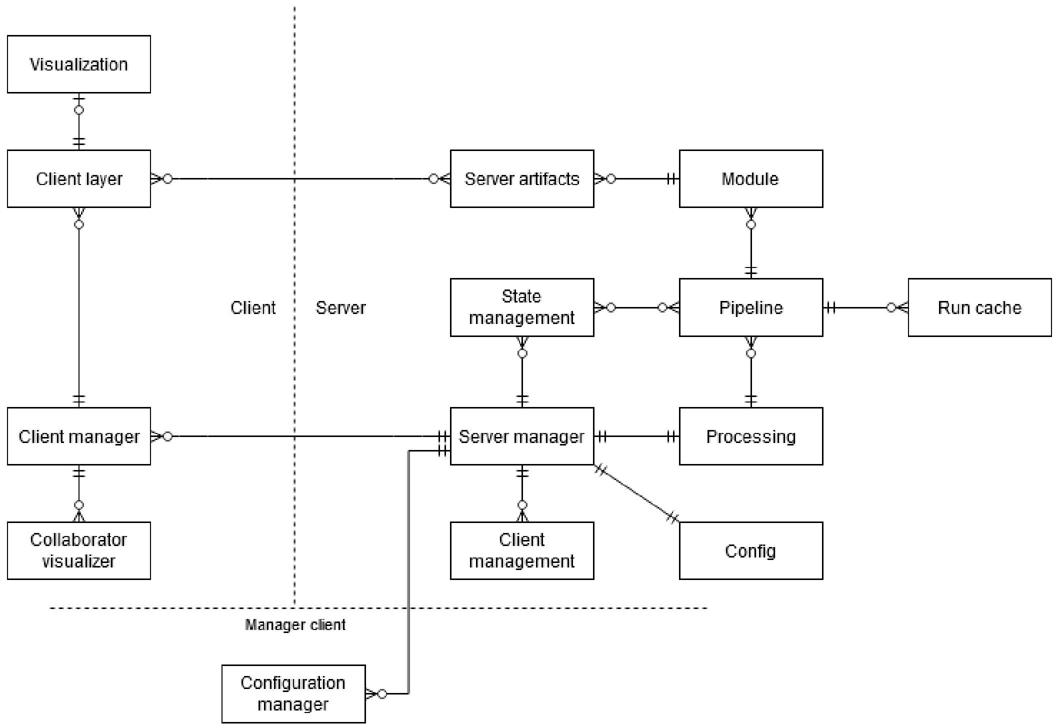


FIGURE 3.2: Relation between the core components

on the previous one. This is also where caching can be applied (see run cache).

- **Module** - Small and specific ways of processing input data. Based on the configuration a pipeline decides which module to run and what data to provide. With a module system the application can be extended to handle other kinds of processing, data or visualizations.
- **Server artifacts** - Holds data artifacts produced by the modules. Artifacts can for example be source files, processed and normalized files, or visualization definitions. Each artifact can be requested separately by the client to improve performance.
- **Run cache** - A cache which pipelines will automatically load and keeps information of previous runs. With this information a pipeline can decide to skip the processing and serve the cache in order to improve performance.
- **Client management** - Manages all the connected clients and keeps track of their position and actions.

- **Client**
  - **Client manager** - The client core which keeps the connection with the server and receives state and configuration updates.
  - **Client layer** - Instructed by the client manager based on the server state. Depending on the state and configuration, it might fetch artifacts from the server which defines the layer.

  - **Visualization** - A visualization of the layer which is managed by the layer. Each layer can only visualize one data set in one configured way, but can apply multiple visualizations to it. A visualization can be of various properties which can be configured, like color and height.
  - **Collaborator visualizer** - A special visualizer to show other collaborators. This is part of the real time collaboration experience and not a part of the configuration and data processing. Hence, this is a special component.

- **Manager client**
  - **Configuration manager** - The web application which displays the current configuration and state of the application. It allows for most of the configuration to be edited and send to the server for updating.

This architecture covers all basics to create a proof of concept application. Every component mentioned in the list above, can be implemented in a minimal way to give validity to the proof of concept. Some more specific use cases are not covered in this architecture, like voice communication, street view imagery, and data annotations coming from the client. These are all not an integral part of the proposed architecture, and can later be added.

The next section will define the models around this architecture which are important for it to work correctly.

3.4 Models

This section enlightens the important internal parts of the above introduced architecture. These are the models for handling the data, defining the configuration and structuring the processing.

3.4.1 Data model

The data model designs what information is to be captured into the application. This information is critical to the systems functionalities and has to be stored. A representation of the data which has to be captured, is shown in the model in figure 3.3. How and when this is exactly stored is a concern of the implementation.

Important parts of this model are the server and client instances as well as the objects. The instances on both the client and the server side capture the state and configuration of the system. This is mostly important during run time to make the application deterministic based on those two factors. For improved performances the state information can be cached as part of the system implementation. The objects are the spill of the data within the system. They are available in various formats, depending on what kind of data it is. The types of input data will be discussed in the next section. Object information has to be communicated with the clients and authored in such a way that it is the same for every client. Each client will hold a mirror of the original object, which is linked by its unique identifier (id). To avoid inconsistency in the data, changes on an object can only be done by one client at the same time and hence are locked by the server through locking exactly one object with exactly one client. Multiple objects may be edited at the same time as long it is done by different clients. The data captured by an object will amongst others tell the client how to visualize the object. Such a visualization might be defined by the configuration by using the properties of an object, which are externally defined characteristics of the data object.

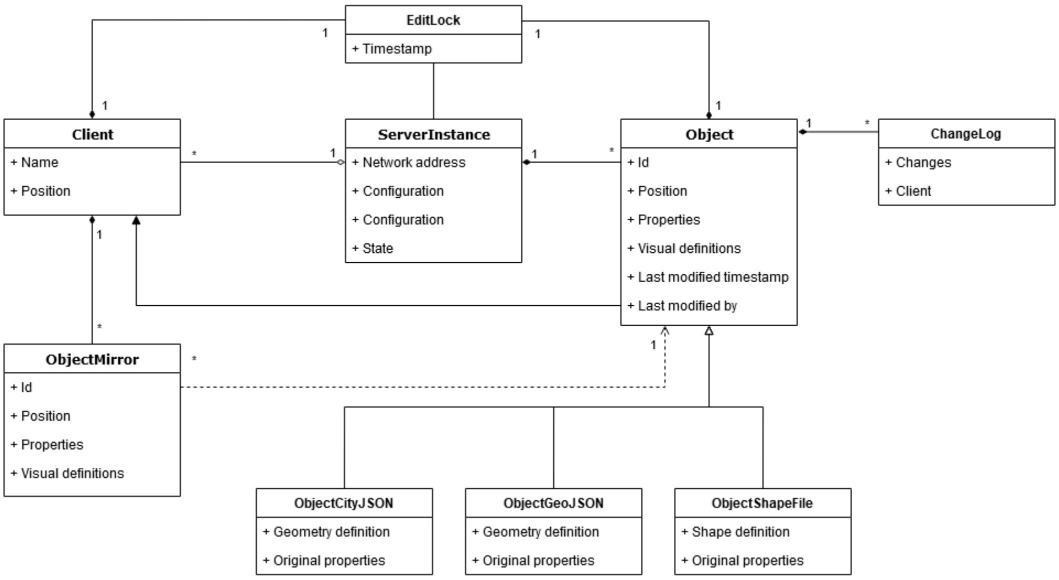


FIGURE 3.3: Data model describing the information captured within the application

Input data

Source data can come in various format which all need to be supported. Firstly the data has to be divided into 3 categories: parametric data, 2D data, and 3D data. For each category a standard way of processing is to be used internally. The basis for saving and passing all the data around will be JSON. For the parametric data every object is a JSON object where one data source consists of a JSON array with multiple objects. For 2D and 3D this structure is roughly the same, however the basis is a feature type object instead of an array and each object is making use of the GeoJSON or CityJSON standards, respectively. Other input data which is to be supported, like Shapefiles, are transformed to one of these standards within the first steps of processing.

Because all these objects will be the core of the visualizations and might need to be updated with changes, every object needs to be tracked. Within the first steps of processing every object has to receive an unique ID by which the client and visualization components can refer an object.

In code block listing 1, and example of a very simple GeoJSON data set is shown. This data set consists of just one object, which is rendered as a single point. In the Evaluation chapter, data like this is used to render the points as spheres. Likewise, other data structures like CityJSON look very similar.

3.4.2 Configuration model

To make the application a parametric tool which supports as much customization as possible, a good configuration model is necessary. The research of Vega-Lite and Reactive-Vega was used as a basis to create a JSON defined configuration definition

```json
[
  {
    "type": "Feature",
    "properties": {
      "connected": 39,
      "status": 2
    },
    "geometry": {
      "type": "Point",
      "coordinates": [
        51.9997871,
        4.3691446
      ]
    }
  }
]
```

LISTING 1: GeoJSON example input

which supports the requirements of this system. This JSON file holds all the information for the whole system to run. Only the data sources are a dependency of this configuration and if one or more are not available for any reason, it will not fail the rest of the system to run.

The following items are possible properties within the configuration file. Most of how it is defined, is based on Vega-Lite.

- **Sources**: The configuration for the input data as discussed above. This does include pre-processing, normalization, simplifications and enhancements. These are the configurations which are less likely to change, because after data is loaded, research is generally more interested in filtering and changing the visuals.
- **Filters**: These define how and if the sources are filtered. Any data which is excluded by the filter, does not have to be processed further. This is more likely to be changed during usage, and hence has its own configuration.
- **Layers**: These are a combination of visualizations from one of the data sources defined before.
  - **Visualizations**: As part of a layer, these decode the items in the source data into visualizations. Generally they will take a field from the data and map it to a property, like position, height, size or color.

An example of what the configuration file could look like, is shown in code block listing 2. This would process an input source like the example in listing 1, transform it to another coordinate system for correct placement, and apply some normalization, simplification and enhancements. All these steps are part of the source, because after the initial render, those values are not likely to be changes. Within the processing model in the next sub-section, these configuration properties are separate pipelines.

```json
{
  "sources": [
    {
      "name": "Useful name",
      "type": "shape",
      "input": {
        "type": "file",
        "path": "data/dataset.geojson",
        "cordSystemType": "RD-NL"
      },
      "normalize": {
        "type": "geojson",
        "typeOptions": "fromGeojson"
      },
      "processing": [
        {
          "type": "simplify",
          "tolerance": 0.5
        }
      ],
      "enhancement": [
        {
          "type": "area"
        }
      ]
    }
  ],
  "application": { ... },
  "layers": { ... },
  "filters": { ... }
}
```

LISTING 2: Configuration example

3.4.3 Processing model

Figure 3.4 shows the data flow within the application when the configuration changes ("Client triggered config update"). The main modules can also be seen in the entity relation diagram (figure 3.2). The processing continues as long as there are pipelines and modules to processes. During the processing, data flows towards the client and caching on various places. Every pipeline and module should be aware of the caching state and the relevant configuration for the module. With this information the actual processing can be skipped in case nothing has changed, which lowers the processing time on small configuration changes. Based on the state send to the client, the client can decide to update the visualization.

Within the flow of figure 3.4, the modules are controlled by the configuration. Everything in between the configuration and the modules is considered to be the framework this work introduces.

Modules handle a very specific kind of processing and are put in place to be easily extendable. New modules can be added to extend the functionalities of the whole application in every step of the pipeline. For example, new filtering functions can be introduced, or a module to map custom input data to a format the client can render. This model makes the application a true framework due to it being extensible.

Additionally, the activity/sequence diagram in figure 3.5 shows an example how a arbitrary configuration and implementation act over time. Based on the configuration, data from sources will flow through each pipeline where it potentially will be processed by one or more modules. The modules can produce artifacts, which the client can use. Based on what was done in a pipeline, the state of the application is updated. Once all pipelines are done, as can be seen in the figure, the processing comes to an end and the clients are given an update.

3.5 UI mock-ups

The UI mock-ups are used to give a general idea of what kind of application is envisioned to solve the problem in this thesis. It shows how the visualization client application, which renders the 3D environment, will look like. This application is meant to be used in an immersive Virtual Reality way with a Head Mounted Device, but can also be displayed on a normal screen.

Within this application the UI interactions are also done in the virtual immersive world. These are not displayed in an overlay as that is not possible when using a HMD. Figure 3.6 shows a general view of the application with two clients connected. Each client will view the map from a physical standing or seated position of their own choosing. The square is mimicking the paradigm of a table with a physical model on top. With their controllers they should be able to move freely around the table, just like in the real world.

When selecting an object in the virtual world, information about the object will be displayed hovering over the object, which is only visible for the client selecting the object. Any interaction with the objects is synchronised to the other clients, which allows the other clients to see what everyone is doing. For example by placing a small hovering text above an object which someone else is viewing. If the user wants to edit some basic configuration, like filters and visualizations, the UI will be reachable

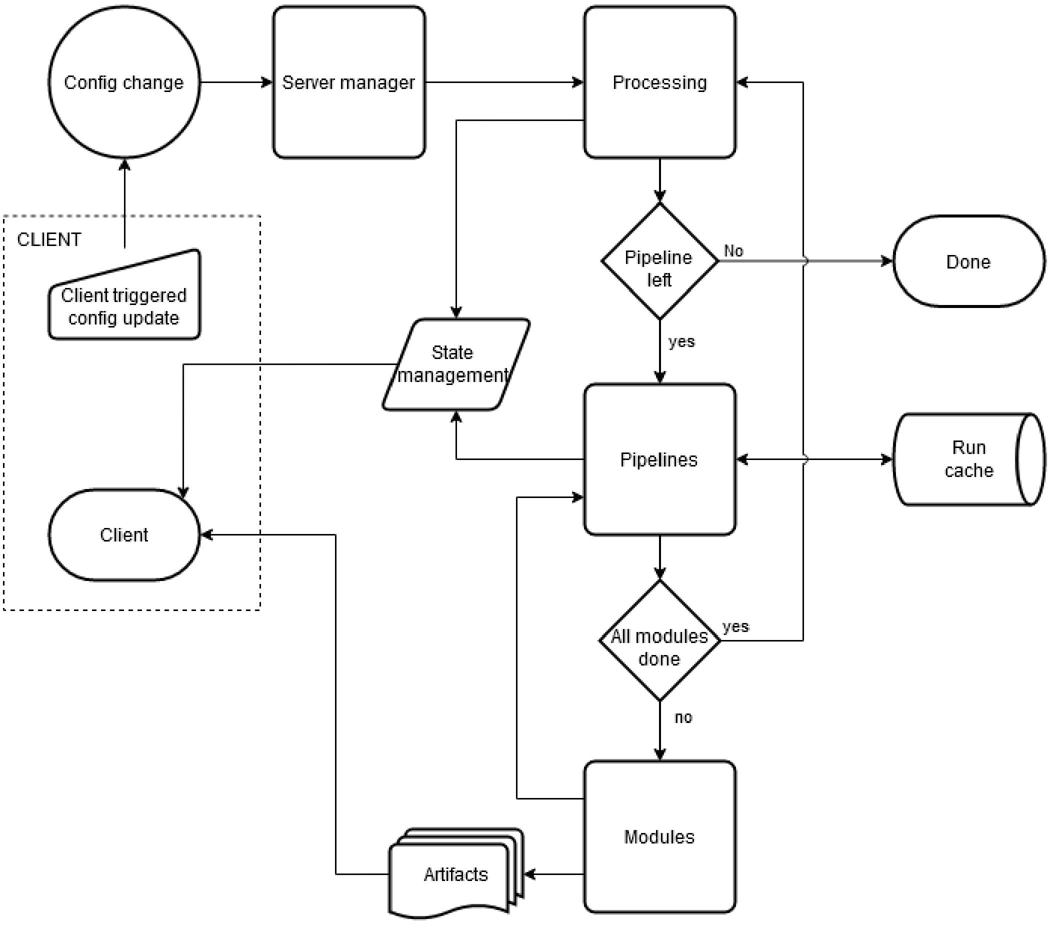


FIGURE 3.4: Shows the data flow when the configuration changed.

on the virtual wrist of the user. This is a very common pattern to access controls in virtual reality, through mimicking a portable device like a tablet.

3.5.1 Configuration Manager UI

Additionally to the data visualization client, there will be a manager application for setting up a configuration. Before heading into the immersive world, the basics can be configured in this manager. Especially defining and importing the data sources is something which is unpractical to do in the immersive world. The mock-up in figure 3.7 provides a rough idea of the start page of this manager. Editing one data source should give a dialog where all properties, as seen in code listing 2, can be edited. The same goes for layers, filters and visualizations.

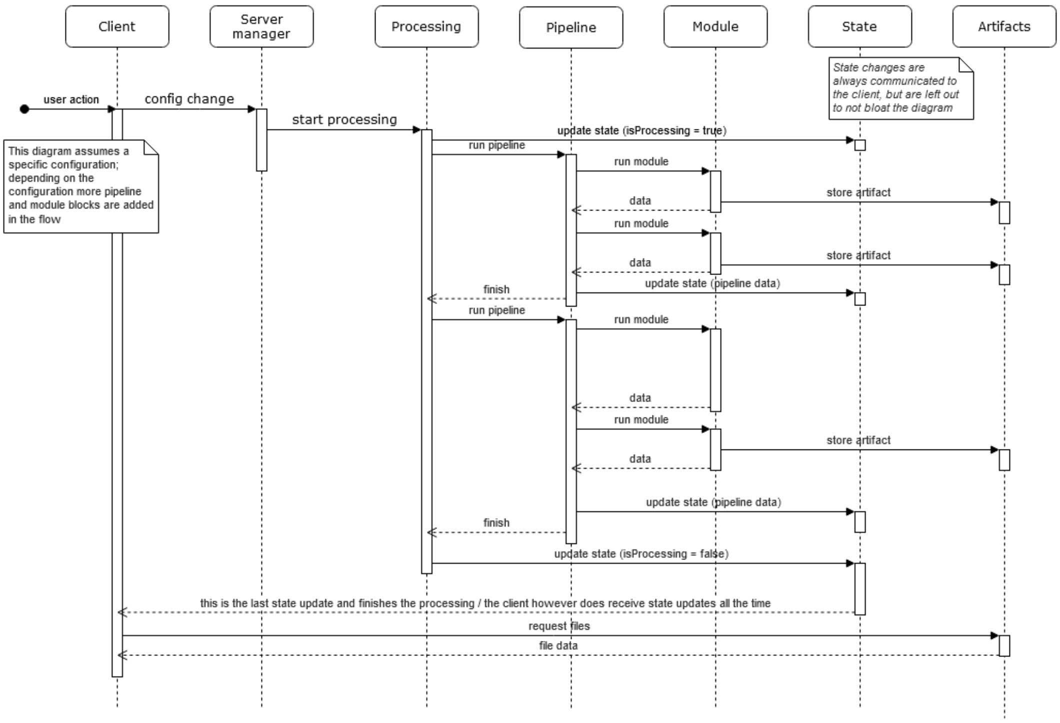


FIGURE 3.5: Activity diagram based on an arbitrary configuration and implementation, showing a configuration change.

FIGURE 3.6: Basic view of the visualization client, giving a rough impression.

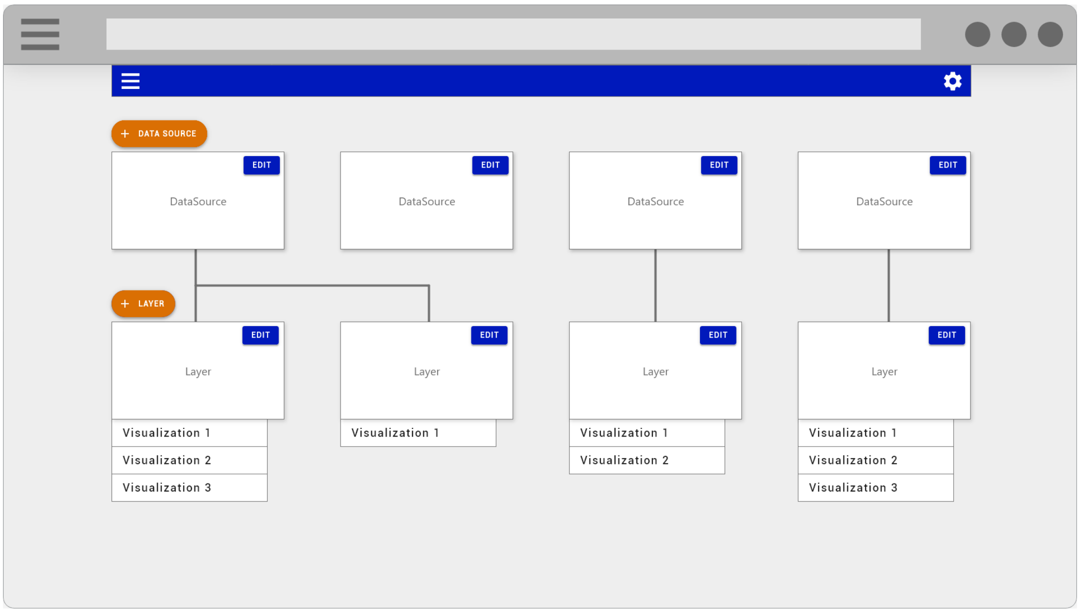


FIGURE 3.7: Basic view of the configuration manager, giving a rough impression.

Chapter 4

System Implementation

In this chapter the design will be put in practise. The various steps of the actual implementation are discussed as well as how they relate to the design and what problems were encountered. Each code-base will be discussed separately in their own section. In each section the most important components will be highlighted and explained in more detail.

The code is available on GitHub, including client builds. See the releases page for a Windows download of the build. General instructions can be found in the `README.md` files.

https://github.com/mikroware/Thesis2023

4.1 Server

The server is build as NodeJS application and is the core of this system. This programming language was chosen because it has a large user base and supporting packages exists for processing of the data intended to be used in this system. Another language with the same characteristics would do just as well. In the core of the system modules were added for JavaScript to support ES6 functionalities like classes for the application to be build in an Object Orientated manner. Standard libraries and NodeJS functionalities were used for communication, processing and file handling.

State and configuration serves as input for the pipelines, while pipelines on its turn, can change the state. State changes are communicated to the client. A run of the processing pipelines can only be triggered by a configuration or data source file change. The processing runs in a separate thread to not block state changes and communication. More details will be discussed in the respective sub sections.

4.1.1 State

The state system is build around a deterministic store without side effects, which makes the state changes and implications predictable. The library used for this is Redux, which makes the state controllable by dispatching actions. Various sub states are created for the different parts of the system during startup. Amongst others, these states are used to keep track of configuration state, current global system state and processing state.

For each state a so-called reducer is used to control the state changes. Each state change can be triggered by predefined actions, which can be used anywhere in the system. To communicate some of the state changes with the clients, every state has a management class which can provide custom behaviour. This class can subscribe to state changes and perform custom side effects, like notifying all clients through the socket connection about the change.

Every part of the system can make use of this global state to read the information it needs. The same goes for all the actions which can change the global state. These can also be send from everywhere. Within the processing pipelines only actions are dispatched and no information is read, as otherwise the processing will be unpredictable. The processing fully depends on the state and other information at the start of the processing, which will be further explained in the pipelines section. Dispatched actions from the processing pipelines are however used in the other parts of the system to perform side effects and other actions.

4.1.2 Configuration

The configuration model was inspired by Reactive-Vega and mostly follows the design as was discussed in the previous chapter. During the implementation process it became more clear why the Vega method of splitting data sources and visual encoding is important. Especially when considering how the configuration and data is processed through the pipelines, it makes it easier to manage the application state, use caches and only update results for changed configuration parts, when the configuration for the various pipeline steps is split as much as possible.

To support the configuration options, it is structured in a "json-schema"[1]. The main schema references all the schemas from the modules, which is explained in the pipelines section below. With this schema, it is possible to validate the configuration file and makes direct editing easier as it shows if the changes are valid. From this schema a JavaScript typing file is generated, which helps with auto completion in the code.

Having these schemas and typing, makes it possible to dynamically show controls for a client to use. Currently these controls are partly implemented in the manager application. For future work, they should also be implemented in the client for easy control. Having this dynamically available, makes it possible to add new modules and directly be able to configure it in the manager or the client without additional coding. This makes it possible for client to update parts of the configuration through a simple layer of communication and validation. When the configuration is updated, it triggers a run of the processing pipelines, which on its turn will trigger the updating of visualizations in the client, effectively completing the circle.

4.1.3 Pipelines

Pipelines are the term used for the various steps in the processing from the input data till it leaves the server. Every processing step has its own specific input format and delivers a specific output format. This makes it possible to connect multiple pipelines to each other and execute them based on the results of a previous pipeline. These predefined formats of internal communication also make it possible to implement automatic caching to speed up processing when only a small part of the configuration or input has changed.

[1] https://json-schema.org

```json
{
  "$schema": "http://json-schema.org/draft-07/schema#",
  "properties": {
    "type": {
      "enum": ["single"]
    },
    "singleColor": {
      "type": "string",
      "format": "color"
    }
  }
}
```

LISTING 3: Example of the configuration scheme of a very simple module, encoding a color to single input value

Each pipeline extends a base pipeline class, which implements all shared logic. It holds base functions for handling pre-processing (deciding if it should run or use cache), processing (the actual processing using modules and other logic), and post-processing (passing results to the next pipeline). If a pipeline has sub-pipelines, it first does its own pre-processing and processing, before running the sub-pipelines. Once all sub-pipelines are done, it calls its own post-processing.

Below a list of the pipelines which were implemented. In future implementations, these can be extended to split the processing even further and improve performance by caching more.

- Pipeline1Source - Wrapper for the sub-pipelines
- Pipeline1Sub1Input - Reading the input data and storing it
- Pipeline1Sub2Normalize - Normalizing the input data to a format which can be use by the rest of the processing and the clients.
- Pipeline1Sub3Properties - Handling the properties of the input data objects.
- Pipeline2Layers - Layers have visualizations, which are created here.
- Pipeline3Filter - Handling of the data filtering.

All the pipelines make use of processing modules. Depending on the configuration, pipelines need to handle their input data in various ways. These small processing modules make it easier to extend the application at a later moment. Every module also has a configuration schema which is used to automatically extend the main scheme. This way it is possible to validate and dynamically update configuration without being dependent on the implementation of every module. Every type of module has its own expected input and output data. How the input is actually processed within the module does not matter for the output and the other components. Code listing 3 shows a configuration example of one of the modules for setting all objects to a single color. The implementation of this module is shown in code listing 4.

```
export default class VisualColorSingle extends Module {
    static type = 'single';
    static name = 'Single color';

    static schema = require('./VisualColorSingle.json');

    singleColor;

    run(){
        // [color, opacity]
        return [this.props.singleColor, 1];
    }
}
```

LISTING 4: Example of a module, which the pipeline can call depending on the configuration

4.1.4 Communication

Most of the communication is done through a socket connection. This will instantly update all the connected clients when information regarding the processing, pipelines or application state changes. Clients can, depending on their own state, use the incoming data to for example trigger an update of the virtual world or present some information. The socket connection is only used to send state, instructions and visualization information to the client.

Additional to the socket, a simple REST API[2] server is used. This server has endpoints for the client to fetch processed data files, which hold the data of all the objects. These files can generally become rather big, which is why they are not being send by the socket connection directly. This keeps the socket connection responsive and allows client data to stay synchronized.

The REST API also provides endpoints which the clients (or manager) can call to update the configuration. Using the REST API for this, makes it possible to let the client know if the update succeeded or if there was an error in the validation of the new configuration.

4.2 Client

The client which will visualize the data from the server is build with Unity. Before making this choice a Javascript WebGL framework named ThreeJS was tried as it was closer to the server code and makes the onboarding easier as everything is on the browser. While it was rather impressive how much could be rendered with this, it had a few drawbacks. Within ThreeJS and WebGL there is not much support for UI within the virtual world. Most interfaces are build as overlays, which is fine for screen applications, however, with the goal of using the application in Virtual Reality, overlays are not an option. WebGL does provide Virtual Reality support, but the tools and libraries are not yet on the level as with for example Unity. Since

[2] https://www.ibm.com/topics/rest-apis

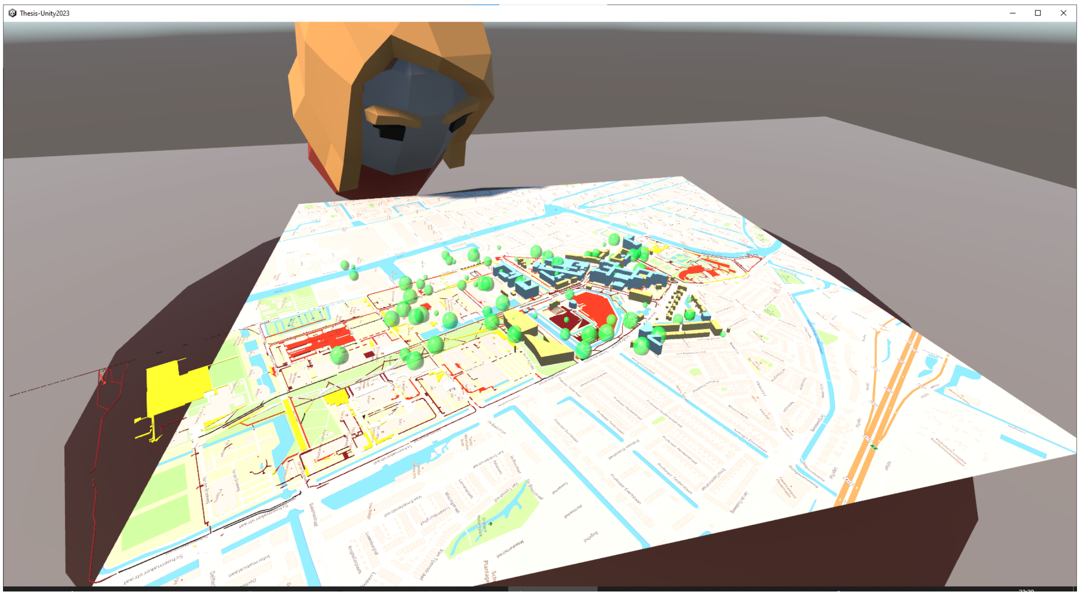


FIGURE 4.1: Screenshot of the client application in "pancake" mode, showing the visualizations and another user being connected.

Unity is a free and widely used engine for all kinds of visual applications, it was picked as the way to build the client application.

In Unity various game objects with a multitude of attached components/scripts are used to build the whole application. Every script is responsible for a separate part of the system, for example synchronising the clients, managing the state, collecting metrics, or managing the map. The most important script is the "DataManager", which controls the whole application. It connects with the socket of the server and acts when data is received. This is where the visualizations are processed, created and updated.

The application can both be used in virtual reality (stand alone on a Oculus Quest 2) and on a computer with the "pancake" mode. In both cases the same exact rendering happens, just in another viewing mode and with other controls. Figure 4.1 shows the application being ran on a computer in "pancake" mode. As will be further explained in this chapter, this proof of concept follows all the requirements, making the framework feasible. In future work improvements can be made to make a full application.

4.2.1 Visualization

Data from the server is received through a socket connection. At startup it will receive the current system state, including all information necessary to start the visualization. For each of the sources, their data files are fetched through the REST API. Depending on the type of data, they are processed by the respective renderer. After the Unity game objects are created for each object, and the meshes are added, it is added to a list of managed objects. With this list and an ID, the object can be targeted to apply visuals and filters.

The meshes of the objects can be generated in various ways. For simple data points, currently the mesh of a primitive sphere object is used. GeoJSON is processed by using an external library which can create an (extruded) mesh from coordinates. 3D object data with sets of 3 coordinates, are converted to a mesh using custom code, which loops the coordinates and creates vertices, triangles and normals.

During usage, new instructions about how to visualize the objects can be received. The received visuals, like color, size or height, are applied to all the objects through the list of managed objects. Because the existing objects are used, there is no need to re-create them, which is more performing. The same principle applies to filters, they enable or disable objects based on the received updated object statuses.

4.2.2 Virtual Reality

As mentioned, the application was build to be able to run in 2 modes. For VR different controls and interactions are added. The user can freely move around the virtual table. Either the VR headset is used in a big enough physical environment to support actual walking around, or the thumb-sticks on the controllers can be used to move and turn. This means the application can also be used in a seated position. Figure 4.2 shows that in VR it looks the same as in "pancake" mode. The only difference here is the beam showing where the controller is pointing.

For this proof of concept, limited synchronisation was made. The position of the camera/head is shown to the other users. Pointing at something is not synchronised to the other users, which could be very useful. Also other interaction is implemented in a limited manner with a few buttons on the wall. This should be extended and integrated better.

4.2.3 Interaction

The interaction is still very limited in the implementation. Both on VR and "pancake" mode it is possible to view data from an object by clicking it. A view will pop up on the place of the object, showing the information, which is shown in the figure 4.3. The selected object is also synchronised with the other clients in order to show a name above it. Buttons on the wall (or keyboard for "pancake" mode) can be used to zoom the map. Also the zooming is synchronized, so all users are looking at the same view. Lastly a few examples of changing the configuration have been implemented as buttons (this can be seen in the virtual reality screenshot in figure 4.2).

Even though the available interaction features are limited, it does check all the points of the proof of concept, as it shows all requirements are feasible. As already mentioned in the virtual reality section, there are various improvements possible for future work. The most important part is by adding more configuration options and rendering it as a personal tablet for example.

4.3 Management client

The management client is a simple ReactJS one-page web application which runs in the browser. It communicates with the server just like the (visualization) client does, however it does not receive visualization updates neither will it download data files. This web application will display the configuration and status of the system in an easy and simple way. In addition to viewing, the management client can also be used to change most of the configuration through the REST API of the server.

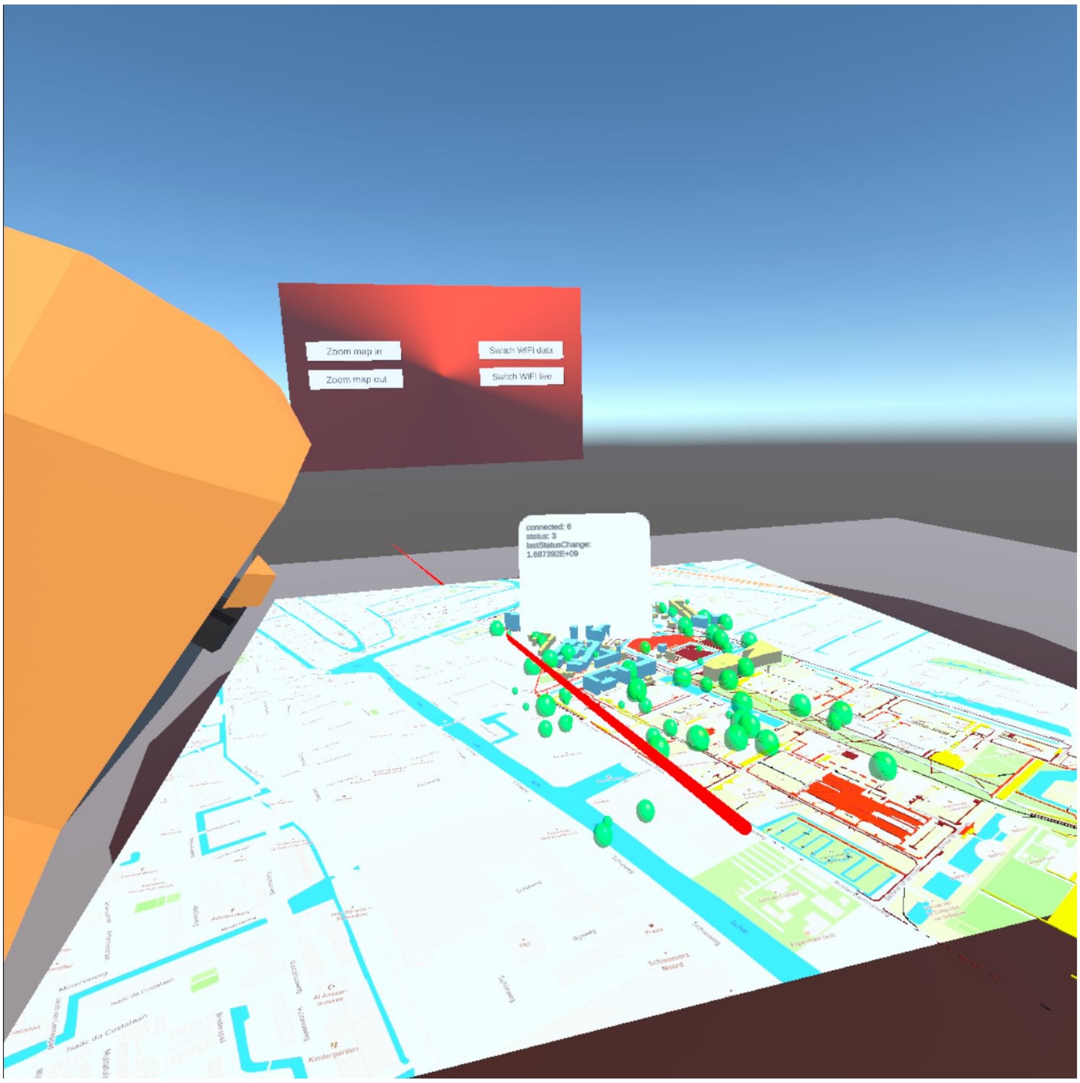


FIGURE 4.2: Screenshot from inside the VR application, showing the same as in "pancake" mode, but a different angle from figure 4.1.

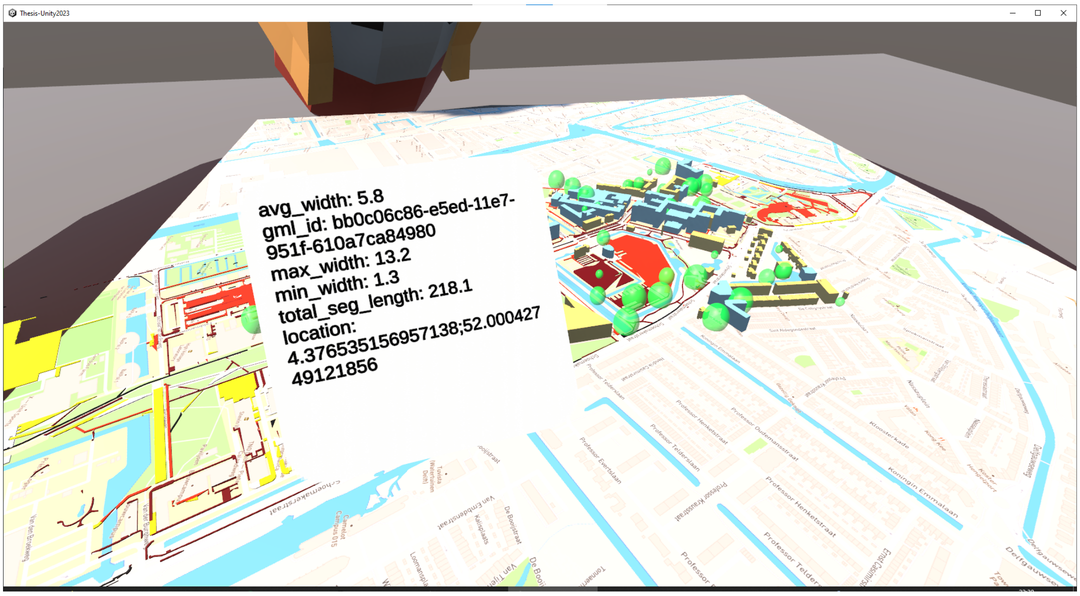


FIGURE 4.3: Screenshot of the user selecting an object to show the data it holds.

One important use for the management client is to import data and set up the basic configuration. This is something which is hard to do while in a virtual world and would be more useful when it is done prior to entering the virtual world. The basic configuration for each data source is generally done only once.

The screenshot in figure 4.4 shows the main page of the management client with a few data sources shown. In figure 4.5 an example of editing the configuration of a module is shown, in this case changing the color mapping where the options come from the module schema. This proof of concept shows it is possible to create a management client to update dynamic configurations and should be build further in future work. The application can also present some metrics on how the processing and pipelines are running, as shown in figure 4.6.

4.4 Example usage

The implementation does not yet live up to the full potential, but is a good proof of concept. Within the current application a lot is possible already. 2 examples are presented to give an idea about the possibilities.

Example 1: Using the TU Delft campus as location. Take data about walkways and buildings from the Dutch government public data set. On top of that render sensor data from the TU Delft. This could be wifi data to visualize how busy areas are. Or for example temperature sensors and have a closer look at the buildings on the campus. Other sensor data could be power usage and power production from solar panels around the campus. On top of that, the sensor data can taken from a real-time source and update during usage of the application. This could pose an easy framework for the TU Delft to view their sensor data, for either researchers, general staff, or students. The setup in this example is roughly what is used in the screenshots throughout this document and also the basis for the evaluations.

Example 2: Use public government data sets on a higher level as example 1. Show for example public neighborhood data of the whole Netherlands and visualize the

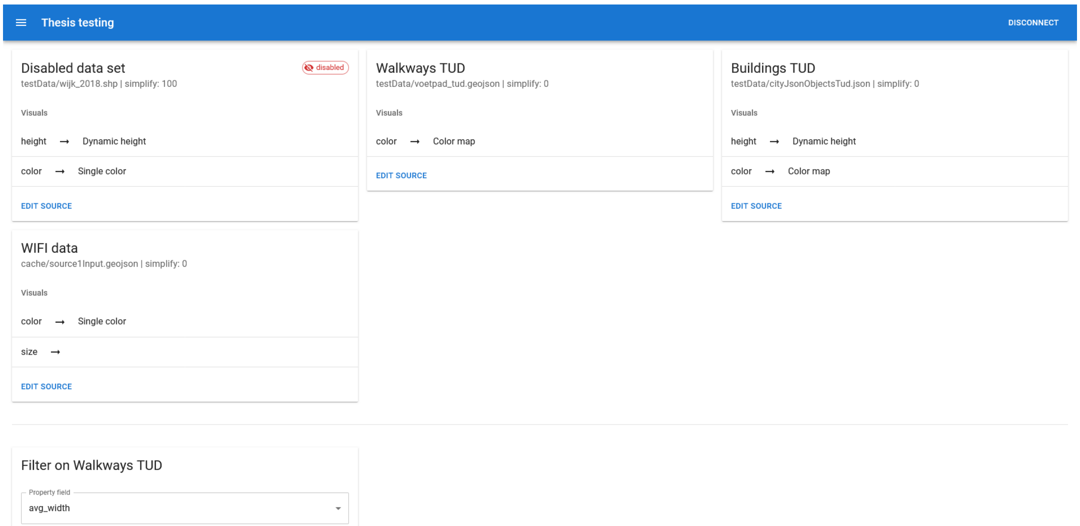


FIGURE 4.4: Screenshot of the dashboard of the management client, showing various data sources and options to change configuration.

heights and color of the shapes. This could be a good way to also include novices in the data analysis as the 3D view in the application makes it easier to understand urban data and place it in context. When extending the proof of concept just a bit, annotations can be made possible. This would allow all the users, including the novices, to easily leave their annotations and perform some data collection tasks.

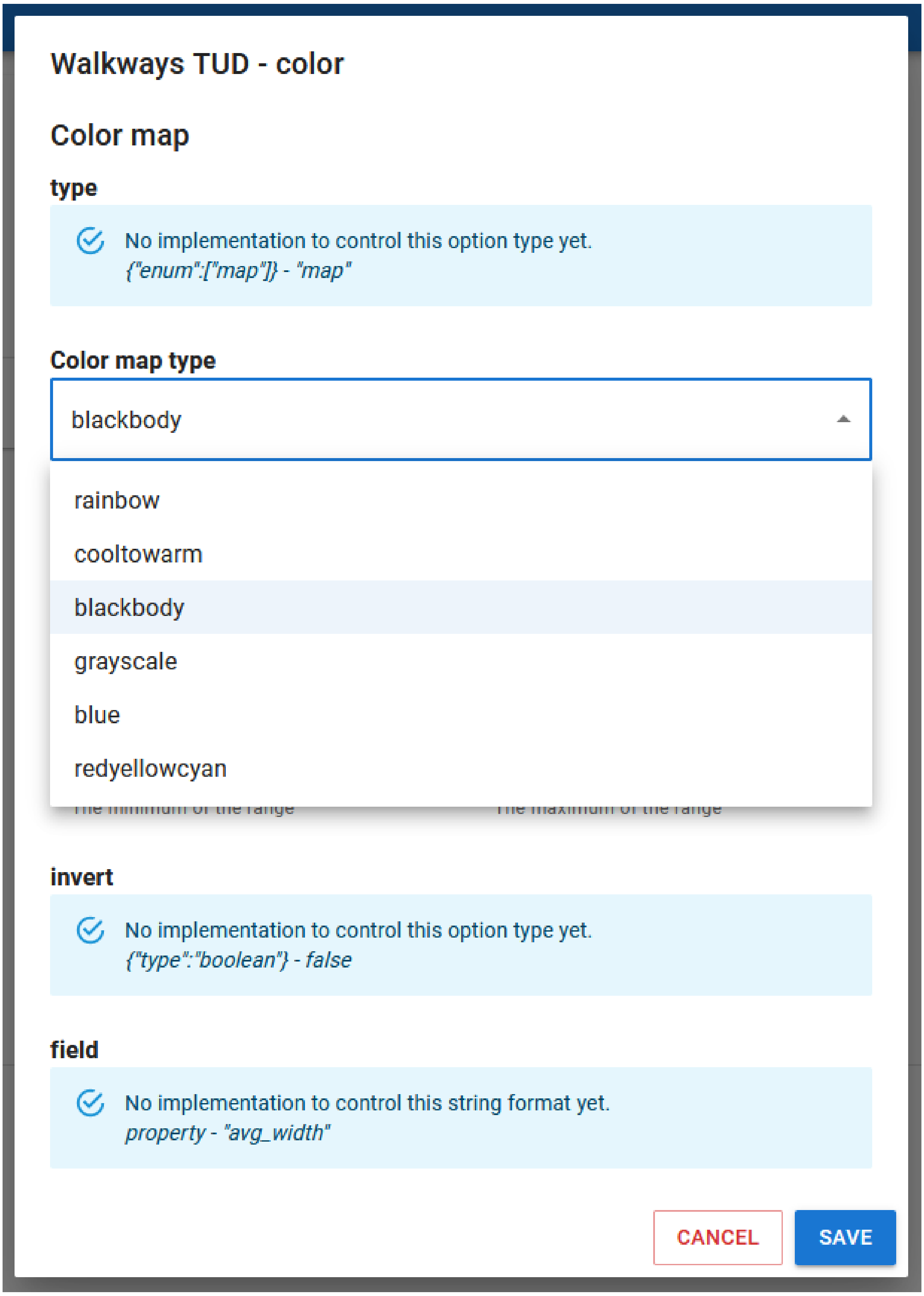
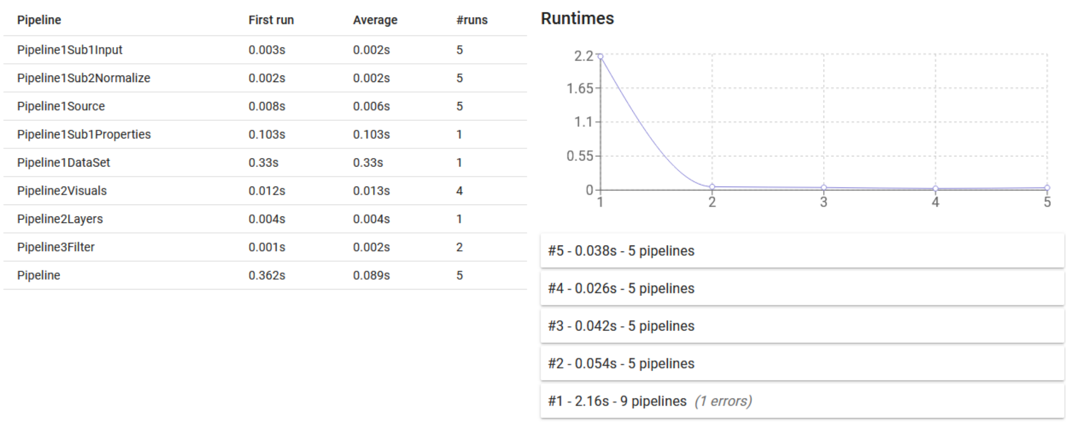


FIGURE 4.5: Screenshot of the dialog to change configurations on the management client, showing how the color mapping can be changed.



Pipeline	First run	Average	#runs
Pipeline1Sub1Input	0.003s	0.002s	5
Pipeline1Sub2Normalize	0.002s	0.002s	5
Pipeline1Source	0.008s	0.006s	5
Pipeline1Sub1Properties	0.103s	0.103s	1
Pipeline1DataSet	0.33s	0.33s	1
Pipeline2Visuals	0.012s	0.013s	4
Pipeline2Layers	0.004s	0.004s	1
Pipeline3Filter	0.001s	0.002s	2
Pipeline	0.362s	0.089s	5

FIGURE 4.6: Screenshot of the metrics page of the management client, showing the runtime of a session.

Chapter 5

Evaluation

This chapter will evaluate the implemented application on performance and by expert users. For the performance evaluations various metrics and scales will be used to be able to make a conclusion in relation to the problem description and research questions presented in the introduction, as well as in relation to what the related work showed. These evaluations will show how the application performs and if it functionally does as was intended. The evaluations consist of predefined metrics, an experimental design and the results.

Additionally a more detailed expert opinion will be presented and the usage of the application in various example cases will be discussed. These last sections will provide a more subjective evaluation on the application, but a more detailed one.

5.1 Performance evaluation

The below metrics are used to evaluate the quantitative performance of the application. These basic measures will show how responsive the application is in both the client and the server side. A responsive application is considered an important part of the user experience as it is critical when introducing client induced changes in a collaborative environment.

Metrics

- **Amount of vertices**
  The total amount of vertices present in the data which is processed and rendered at that moment. This gives an idea about the complexity of the data.
- **Amount of objects**
  The total amount of objects in the data which is processed and rendered at that moment. This gives an idea about the size of the data.
- **Amount of clients**
  The amount of connected clients to the server at that moment. More clients will especially mean there will be more communication and more data will be requested from the server. This can impact the response time in a collaborative environment.
- **Pipeline processing time (server runtime)**
  The time it takes for the whole pipeline to run one time and process the whole configuration.
- **Client fetch to render time (client perceived runtime)**
  The time it takes from the moment the client starts to fetch a data set, till all the

data is rendered for the first time. Within this metric a round-trip to the server is included as well as the parsing and rendering of data. Its purpose is to give a good idea of the perceived response time for an user.

- **Client visuals update time (client perceived update time)**
  The time it takes from the moment the client received new visuals, till all the visuals are rendered/updated. Within this metric the time for parsing and applying of the new visuals is included. Its purpose is to give a good idea of the perceived response time for an user when updating a visual configuration.

In order to test some of the server side specific metrics, clients can be simulated without rendering. Avoiding the rendering will make it possible to simulate multiple clients on the same machine without the resources needed for rendering. Client side metrics can be tested with just one client connected to the server.

5.1.1 Experimental design

The experiments for this evaluation will be performed on a server and a client computer which are connected through an isolated network. Both computers will only run the necessary application(s) and will be brought back to the original beginning state after each of the tests. For each of the tests all of the above defined metrics will be collected (in some tests client metrics will be excluded). Exact specifications of the tests will be given in the results section.

Performance tests

Each test will be performed under the same circumstances. Only one input metric/parameter will differ for each test. For all tests the earlier defined metrics will be collected. These tests will try to represent some situations which may occur while actually using the application, which are brought back to simple tests so the results can be attributed to the change of one input metric/parameter.

Each of the tests (except the last one) will only change one of the above defined metrics in predefined steps. Unless stated otherwise, the following defaults will be used for every test.

- One separate client on a different isolated system.
- One manager client on the same system.
- A basic configuration with all the data just used one time and not refreshing. This is to be considered a base line for all tests, and it is thus not relevant what it exactly consists of.
- Depending on what data is collected, the tests are done after the system is started and the first initial pipeline run is done. The successive pipeline runs are the relevant ones for measuring performance as they happen during usage. The initial pipeline run is relevant to measure the capacity of the system.

The following tests will be done for 10 different values for each metric. For every different value, the tests will consist of 3 runs, which will be averaged to account for any deviations from resource availability. Each of these tests will be done 3 times and the results will be averaged to account for any other deviations from the host system.

1. **Increase objects (testing size)**
   For this the amount of points provided in a shape file will be increased. Each point only consists of one coordinate and a few properties. On the client this is rendered as a sphere and has a low complexity.

2. **Increase objects and measure configuration change (testing responsiveness)**
   This does the same as the test above, however, this time the visual update time will be recorded. To do so, a color configuration will be changed which will trigger a pipeline run.

3. **Increase vertices (testing complexity)**
   This increases the amount of copies of a set of complex GeoJSON objects placed randomly within the viewing area. Naturally this also increases the size, but now including complexity as one item does not consist of one point anymore, but a whole set of points to generate a 3d structure.

4. **Increase clients (testing connectivity)**
   This is done by emulating clients on an external system without doing the graphics. Which means no client perceived runtime metrics will be collected for this test. This should give an idea about what the impact of more clients is on the system.

5. **Increase all 3 at the same time**
   Just as the connectivity test, the increase of clients is done by emulation. On top of that, the first client will be a real system with graphics in order to collect the client perceived runtime metric. The other two metrics are increased just like in their own tests. Finally a visual configuration change is triggered of which the data is collected.

In the next sub section the results will be presented through graphs and trend lines.

5.1.2 Experimental results

For the tests the test data files from the code base were used. The code base can be found separately to this document. Except transforming coordinate systems, no additional processing was done on the input data. All tests were done on the following systems:

- **Main system specs:** 64GB RAM, i7-10700K 3800 Mhz 8 cores 16 threads, NVIDIA GeForce GTX 1660
- **Client system specs:** 32GB RAM, i7-1270P 2200 Mhz 12 cores 16 threads, Intel(R) Iris(R) Xe Graphics

The averaged results are presented in appendix A. For each of the stated tests, the graphs are rendered below. Each graph contains a linear or polynomial trend line with their respective R^2 value.

Increase objects

This was done by increasing the amount of objects send by a mock generator through a live connection. Every 5 seconds it updates the properties of all points, and by doing so forces a re-run of the processing system. In total 3 updates are collected after the initial load. What this would visually look like on the client, is shown as example in figure 5.1.

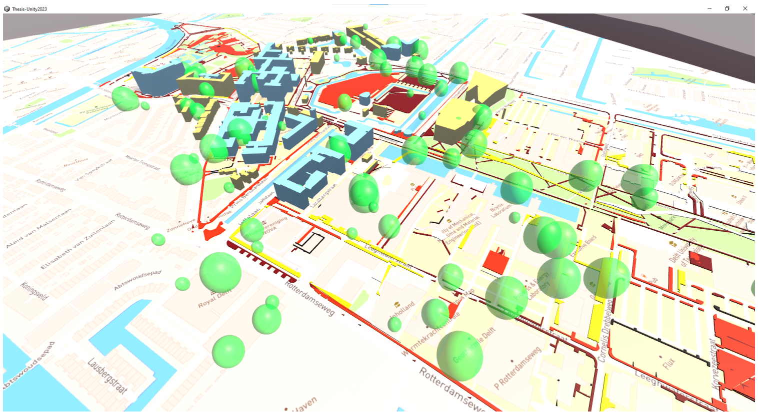


FIGURE 5.1: Example of how a test render with live objects would look like. In which the green spheres are being live updated in size and of which the amount was increased each test.

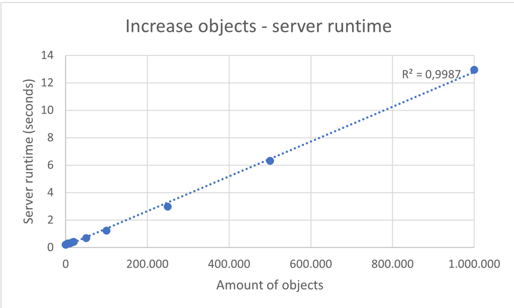


FIGURE 5.2: Increasing the objects and measuring the server runtime

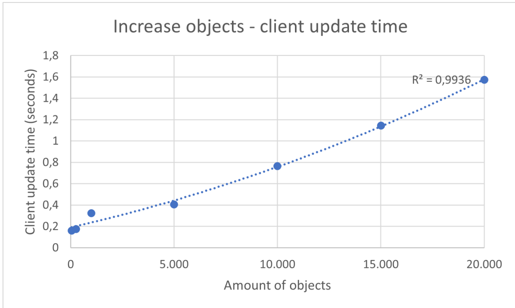


FIGURE 5.3: Increasing the objects and measuring the update time on the client

When trying to load 50.000 objects, the client could not handle the initial load of the objects anymore. Even after waiting over 20 minutes, the client was still busy loading. Hence, in the results the client run times do stop after this amount. The initial performance can most likely be improved by better leveraging Unity to optimize the client. The data which was gathered however, does show changes can be propagated into the virtual world significantly faster than the initial loading.

At the top, when loading 1.000.000 objects, the cached data file was 180MB in size. All this data has to be transferred over the network to the server and to the client. It is quite reasonable that such amounts of data cannot be loaded in the visualization without doing heavy optimization.

The results in figure 5.2 show the server runtime is linear to the amount of objects. This is as expected, considering the implementation of the server does basically only do a simple set of actions for each object. On the client results in figure 5.3 a 2^{nd} degree polynomial relation can be noticed.

Increase objects and measure configuration change

This tests increases the amount of objects and measures the runtimes when a configuration change is made. In this case, the color mapping was changed. This results in no reloaded objects on the client, but only changing the color of the object. How this change looks like for the client can be seen in figure 5.4 and figure 5.5. Just like with the previous test, the client could not handle the initial load anymore at some point. Thus, the results for the client metrics stop after 20.000 objects.

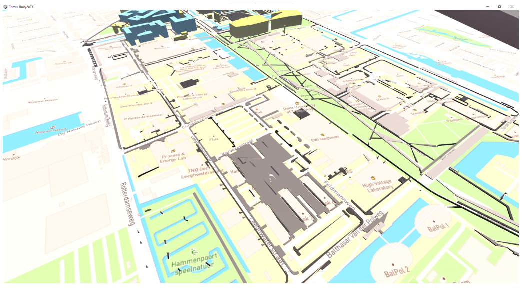


FIGURE 5.4: View of the client before the configuration change (color map "greyscale")

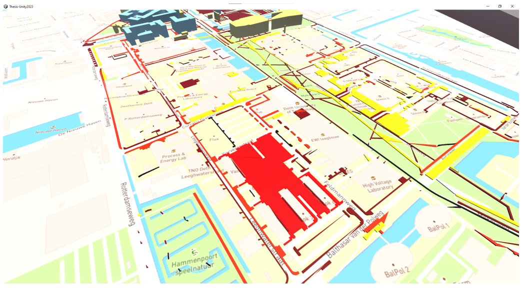


FIGURE 5.5: View of the client after the configuration change (color map "blackbody")

Figure 5.6 showing the results of the server runtime, does again show a linear relation. The same goes for the update time in the client, which is also a 2nd degree polynomial relation as shown in figure 5.7. This again shows that propagating visual representation to the client, is significantly faster than the initial load.

Increase vertices

For this test GeoJSON of polygons is used, which represent walking ways in the TU Delft area. To increase the amount of vertices, and thus amount of complex objects, the data was duplicated. Note that also here the data gets very big, for example the data for the last test was about 400MB. These are sizes which are very much out of the scope and use cases of a system like this.

As opposed to the previous two tests, the client render time of the initial render is measured. This gives an indication on how the clients performance will be if new data is to be rendered during the usage of the system.

Also here a linear relation on the server runtime can be noticed in figure 5.8. The fact that the system has to transform the coordinate system, which does take processing time per vertex, can explain this relation. For the client render time, a clear polynomial relation can be noticed again in figure 5.9. As opposed to the update times in the client (previous 2 tests), these values are significantly higher. The creation of new objects in the virtual environment is very costly and is something to take into account.

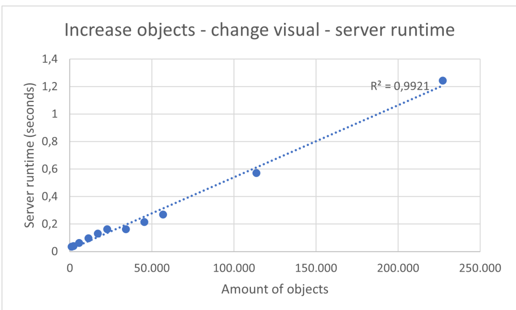


FIGURE 5.6: Increasing the objects, and measuring the server runtime triggered by a configuration change

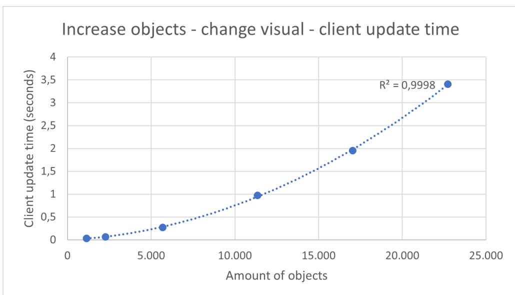


FIGURE 5.7: Increasing the objects, and measuring the update time on the client triggered by a configuration change

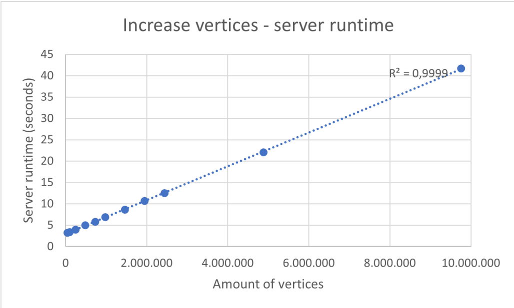


FIGURE 5.8: Increasing the vertices and measuring the server runtime

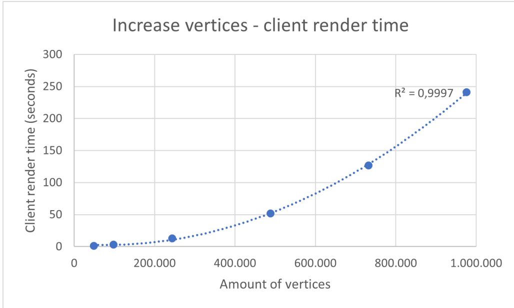


FIGURE 5.9: Increasing the vertices and measuring the render time on the client

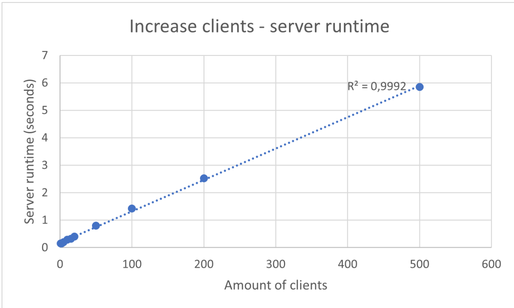


FIGURE 5.10: Increasing the clients and measuring the server runtime

Increase clients

This uses the data from the previous test, but instead changes the color mapping after the initial render. A visual change like that will communicate all its visual data through the direct connection with the clients. The client system was setup to fake multiple clients at the same time. Each client was able to receive data but did not render anything. Because of usage of fake clients, no client render times were measured.

As can be seen in figure 5.10, the amount of clients also has a linear effect on the server runtime. Which gives a good indication what to expect when connecting a significant amount of client. In reality, only a few clients will be connected. This does however show that the amount of client does have an effect on the runtime.

Increase all

This test combined all of the above and increased objects, vertices and clients at the same time. At each point, server and client run/update times were collected for 3 metrics: initial runtime, runtime when new objects were introduced during the run, runtime on update the visuals of the newly introduced objects. The first run in this test with the lowest numbers is roughly what the participants in the 5.2. Expert evaluation section also experienced. The raw data can be found in table A.5.

In general the data shows there is more load on both the server and client, which seems to have a significant impact on the systems as run-times are increasing fast. Figure 5.11 and 5.12 show this compared to the "increase objects" test, which is the most comparable. The orange points are from this test.

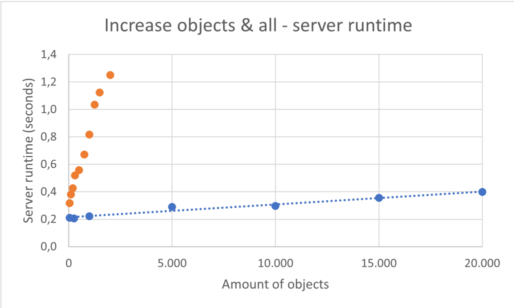


FIGURE 5.11: Increasing all and measuring the server runtime

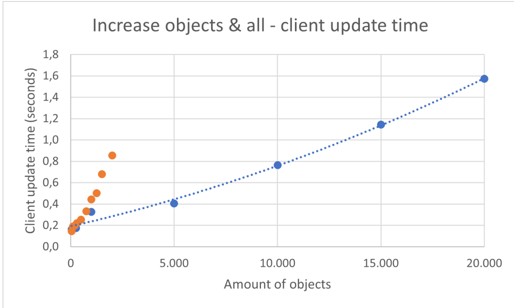


FIGURE 5.12: Increasing all and measuring the update time on the client

This test was done with various variables changing, which makes it hard to attributes the significant increase in runtime. This also means the comparison in the figure is just a rough indication. Further extensive testing is needed to examine the behavior of the system under more conditions, for example through a design of experiments.

5.1.3 Conclusions on performance evaluation

The processing time on the server and propagation of data to the client is linear for all 3 tested metrics within all 4 tests. So, any data handled on the server is linearly processed. On the client, the rendering and update times are a polynomial relation for all 3 tests. Rendering massive amounts of data is performance heavy and could potentially be improved with lots of graphic optimizations. These results were expected due to the nature of the server and client systems.

When data is live or has a configuration change, is has to feel responsive. As literature states, 200ms still feels responsive. In case of live data, client runtime is considered, as that is what can delay responsiveness. Which means live data of about 800 objects still feels responsive. For a configuration change the server runtime plus the client runtime has to be considered (round trip to the server). Since a configuration change (on the color mapping) does have another footprint, changing around 4.000 objects still feels responsive.

On all tests, loading extreme amounts of data into the client, resulted in a long initial load. For 4.000 objects this already took 1 minute. The last test which did successfully load in the client, was 20.000 objects, which took around 5 minutes. Though after creation, the updating of its size stayed very fast, as can be seen in the results above.

When not going into the thousands of objects, the runtime on the server and update times on the client are below 200ms. This means that client induced changes in collaboration is feasible using this system. Which thus full-fills the performance requirements within the context of the functional requirements. And hence, validates the implementation on these aspects fits the design.

5.2 Expert evaluation

To evaluate the overall potential and future direction of this proof of concept, experts in VR and urban analytics were asked to explore the tool. Participants were guided through the tool, after which they were asked to give their opinions on the main benefits and future improvements. A total of 3 sessions were conducted with either one or two experts in the same physical room.

Participants were given a VR headset and asked to follow a guides tour. After using the application, the opinion of the experts was asked in semi-structured interview. Including positives, negatives and potential improvements. These conversations were recorded and transcribed. Lastly the potential of the application was discussed with the experts. Appendix B describes how the sessions with the experts were structured.

5.2.1 Expert results

The opinion of 4 experts was asked in a total of 3 sessions, of which transcripts are available in Appendices C, D & E. All experts are affiliated with the TU Delft and have academic functions. The table below shows the session with their participants, and how they will be referenced later in this section.

Session 1	1 expert *(P1)*	PhD Candidate
Session 2	1 expert *(P2)*, 1 student *(P3)*	PhD Candidate, master student
Session 3	2 experts *(P4)(P5)*	Directors of VR lab P4 is also Ass. Professor

References from experts are either quoted exactly, or summarized to keep this section concise. If a quote is sourced from more than 1 participant, the first one named did say the exact quote. The participants after that either said something similar, or agreed.

Benefits the system provides

In general the experts have given roughly the following opinions and benefits on the system.

- Being able to see the same data together. Even if not physical together. (P1, P2, P3, P4)
- Being able to quickly visualize data. (P4)
- Being able to see the other person in the virtual world, and see what they are doing. (P1, P2, P3)
- Being able to cycle through different visualizations. (P1)
- Being able to look at the data from different angles. (P1, P2)
- Still being able to virtually poke in the data, despite the tabletop setup, which is a good way of contextualizing the physical space. It gives more of a feeling of being in the data than just looking at it from a distance. (P1)
- The distinction between changing configurations outside of VR, and experiencing it inside of VR. (P1)
- Very useful for dynamic data and data with more of a 3D context. (P2, P4)

Improvements

The experts suggested the following improvements which would really help the system. In general improving the UI and controls, thus making it an actual application and not a proof of concept, would increase the usability of the tool.

- "Being able to take notes. So maybe like a whiteboard feature." (P1)
- "Being able to point. I would point to things in real life.", so synchronizing more of the data from the clients to get a better idea of what the others are doing. (P1, P4, P5)
- Integrating with other environments and tools is a good opportunity. For example to show and control models. (P4)
- In general improving the controls could make it "much stronger". (P4)

Notable remarks

Besides the general opinion and improvements, the experts also provided some notable remarks. They indicated various potentials the system could have, as well as some ideas for future work.

- "I think for a proof of concept is very solid." (P1, P5)
- "I think you could also use it maybe as like more community engagement. I think the interactive virtual thing works well for people who are novices with dealing with data." (P1)
- "I also liked the simple thing that you put the buildings as 3D ... to understand where I am because I know that campus area." (P2)
- "I like that you can quickly visualize data. And I think that's an important future feature." (P4)
- "And second thing what I like is that you do live data, so that could be any sensor like temperature. Indeed, amount of people in the room." (P4, P5)
- "Think it's nice if people talk that they can really indicate and talking about this object." (P4, P5)
- "We have so much data which is in 2D, which is hidden in maps, so making it visible in the 3D World is really helpful." (P4)

5.2.2 Conclusion of expert evaluation

Experts were overall positive about the potential of the system from an usability perspective. They suggested various improvements to the interface, virtualization and feature set. As far as they were able to evaluate the underlying technical aspects, they were deemed as being solid.

The suggested improvements would be logical next steps in further development of the tooling. Most of them are about improving the general experience, which should be no problem to incorporate in the system. Adding/annotating locations or rendered objects was already discussed before in this report. Technically the system infrastructure already supports, this because it is able to update data in a live manner. The same goes for being able to use output from models as a data source and being able to control those models from within the VR application. Hence, all suggested improvements are feasible. This proofs the implementation and design are indeed a solution for the research questions.

The system has the potential to be a useful tool for various goals and professions. A few which were named, are urban planners, and people working on community engagement. Additionally, even building managers and students could benefit from this to easily visualize, inspect and collaborate on their data. For some groups this could even support their decision making process. In general the experts conclude there is potential in the system, especially on the subject of live data.

Chapter 6

Conclusions

This subject was introduced as a relatively new and scattered one. There has been quite some interest in the various new technologies, like virtual reality, which has become a part of all kinds of research. In a lot of those cases the application and technology was merely used to research a goal in another domain. Tools to do the research were created specially for each situation and data was in most cases processed manually. This did show the need for a generic tool which takes various aspects into account: Urban Data, Exploration, Virtual Reality, Interactive, Real Time and Collaborative.

Besides identifying the current state of the art, more research questions were answered. Below all 4 parts of this research is summarized and concluded on in their own section. Together they will show it is possible to create a framework which allows for real-time analysis and exploration of heterogeneous urban data in virtual reality, while allowing for collaboration.

State of the art review

As a first contribution, the state of the art was reviewed. This showed some interesting insights in regards to how other research uses their urban data. Not much research did actually try to make a framework which could support future or other research, mostly because the data and interface were custom made for its goal. Other types of research took a deep dive in just one of the aspects. For virtual reality a lot was done on the subject of effectiveness. And for configuration of visuals, work was done mostly in the 2D context. For all aspects included in this work, usage and limitations in previous research was established. This formed a base to build the design upon.

System design

Based on the state of the art, a system design for the framework was created. Firstly by defining user stories and requirements to make sure all needs were documented. An architecture was designed with both a client application and a server application to support collaboration. Within the architecture, components were placed to manage data, states, clients, but especially support processing of data in various steps. Having this processing pipeline with various layers and steps forms the core of the design, which allows for a lot of possibilities. A configuration model was created to control the processing pipeline and other settings. This ensured visualizations can be re-created at any time without manual steps each time the application is used. Lastly an interface for the client was designed, which is build around collaboration and synchronization between clients. In totally, this design creates a fully configurable system.

Prototype system implementation

The system design was used to build the implementation in Unity for the VR client and JavaScript for the server. These languages do seem to perform quite well and also support a lot of utilities. Leveraging more knowledge about Unity, could potentially improve the client performance. For the server a more efficient language could be used. But, for a proof of concept implementation, this was performing really well with live data and configuration changes. This can especially be attributed to the caching of the processing pipeline steps, which try to only run for data or configuration which has changed.

Evaluation by experts and performance

The created prototype application was evaluated both on performance and by experts. On the server application it was possible to process over 1.000.000 objects from GeoJSON data within 10 seconds. After which the cache helped to reduce the processing time on simple visualization changes. Server runtime was found to be linear in relation to the amount of data. Initial rendering on the client was found to be very expensive, but after this, the client application could update over 4.000 objects in an interactive manner of 200ms. Feedback from experts further supported the validation of the proof of concept application as a viable solution to the problem statement. It can be concluded that, within a limit of data, the concept framework is usable, follows the design, and solved the problems in the related work.

6.1 Limitations

This work does have a few limitations. Especially because of the very broad objective, details are still to be researched. To create a full application, future work is necessary. In section 6.2 some of the possible next steps are discussed.

Annotations - There is no full implementation of an annotation feature. While the proof of concept does allow for data from the client to be send to the server, and the server is capable of processing real-time source file updates, a full flow for annotating data was not tested. Because of the other features, it is expected that annotations are feasible within this system.

Real use-cases - The performance evaluation was done using a basic configuration. Of course this was necessary to create a controlled environment to produce valid test results. However, it is unknown how the proof of concept will behave in other and real scenario's.

6.2 Future work

The presented research is just a first step in the direction of a potential complete application. Suggestions for potential future work are presented below. Each of them could help strengthen the conclusions or build further on this work.

- The usefulness/effectiveness of VR, in the use cases described in this work, was explicitly not a part of this work. Separate research should be done to investigate this, which can help strengthen the need for turning the proof of concept in an application.

- Further development of the application by adding more features, accepting more kinds of data and improving the user experience, thus making it an actual application and not a proof of concept. One of the important parts is being able to control more of the visualizations from within the VR environment, for example by adding an interface to the virtual wrists of the user. Adding more collaboration tools was also pointed out to be a great feature to improve the application.
- To proof the validity of the tool and get more angles for improvement, it should be used in real use cases and research. Testing and using the application in actual situations will most likely help to improve the tool quicker.
- The live/real-time aspect of the application is an interesting and new angle for applications like this, as experts suggested. Future work could focus on how to improve this and make it the core of the application. There is a lot to discover and research on this subject, as it could benefit from performance and feature improvements which touch many other aspects.
- It was suggested that allowing input data from computational models could open up a whole new perspective. Especially if the models can be dynamically controlled from within the VR. For example, this would be really useful to add a timescale and visualize what happens over time depending on the model input. Technically this has a lot of overlap with the proof of concept being able to handle real-time data. Improving and extending on that, opens up a clear path to connecting models to the application.
- Working further on this research and the proof of concept with an interdisciplinary team. This would help improve all aspects of the visualization and interface in order to make it an effective application. Not only interface or graphic experts should be included, but also experts from the fields of urban data. Including stakeholders from various domains, could make this tool live up to its true potential.

Appendix A

Quantitative evaluation results

objects	clients	server runtime	client runtime
50	1	0,2108	0,1613
250	1	0,2070	0,1740
1000	1	0,2213	0,3248
5000	1	0,2906	0,4057
10000	1	0,2978	0,7649
15000	1	0,3567	1,1449
20000	1	0,3985	1,5732
50000	0	0,6902	NaN
100000	0	1,2340	NaN
250000	0	2,9744	NaN
500000	0	6,3036	NaN
1000000	0	12,9424	NaN

TABLE A.1: **Increasing objects.** Times are in seconds. Note that after roughly 20.000 objects, the client could not perform the initial render within 20 minutes and hence no further client results are available.

objects	clients	server runtime	client update time
1136	1	0,0355	0,0346
2272	1	0,0400	0,0639
5680	1	0,0620	0,2749
11360	1	0,0960	0,9754
17040	1	0,1295	1,9537
22720	1	0,1618	3,4035
34080	0	0,1625	NaN
45440	0	0,2140	NaN
56800	0	0,2683	NaN
113600	0	0,5715	NaN
227200	0	1,2445	NaN

TABLE A.2: **Increase objects and measure configuration change.** Times are in seconds. Note that once again after 20.000 objects, the client could not perform the initial render within 20 minutes and hence no further client results are available.

vertices	clients	server runtime	client render time
48805	1	3,2308	1,1713
97610	1	3,3870	3,1876
244025	1	3,9625	13,0891
488050	1	4,9488	52,0041
732075	1	5,7717	126,7399
976100	1	6,8453	241,2828
1464150	0	8,6295	NaN
1952200	0	10,6440	NaN
2440250	0	12,4788	NaN
4880500	0	22,0565	NaN
9761000	0	41,6693	NaN

TABLE A.3: **Increase vertices.** Times are in seconds. Note that once again after 20.000 objects (about 1 million vertices in this case), the client could not perform the initial render within 20 minutes and hence no further client results are available.

objects	clients	server runtime	client runtime
22720	1	0,1565	NaN
22720	2	0,1550	NaN
22720	5	0,1977	NaN
22720	10	0,2860	NaN
22720	15	0,3283	NaN
22720	20	0,4018	NaN
22720	50	0,7990	NaN
22720	100	1,4275	NaN
22720	200	2,5248	NaN
22720	500	5,8485	NaN

TABLE A.4: **Increase clients.** Times are in seconds. As described in the evaluation chapter, no client visuals were rendered.

vertices(I)	objs(I)	Cs	objs(A)	SR(I)	CR(I)	SR(A)	CR(A)	SR(V)	CR(V)
48805	1306	1	50	3,2090	1,3742	0,3165	0,2047	0,3195	0,1461
97610	2442	2	100	3,4405	3,1407	0,3810	0,3855	0,3688	0,1881
146415	3578	5	200	3,5995	5,6581	0,4255	0,6448	0,4198	0,1965
195220	4714	10	300	3,7280	9,2718	0,5200	1,1439	0,4813	0,2220
244025	5850	25	500	4,0190	13,7067	0,5585	2,2446	0,5155	0,2516
341635	8122	50	750	4,4080	25,9451	0,6705	4,8059	0,6538	0,3325
488050	11530	70	1000	4,9730	53,2411	0,8165	10,0887	0,8945	0,4420
585660	13802	100	1250	5,2940	75,6795	1,0340	17,5973	1,0250	0,5026
732075	17210	150	1500	5,8060	124,6534	1,1230	26,6154	1,2310	0,6799
829685	19482	200	2000	6,1370	167,0339	1,2500	40,8497	1,3730	0,8543

TABLE A.5: **Increase all.** Times are in seconds. S = server, C = client, R = runtime, I = initial, A = added while client is connected, V = visual. 3 measure moments during a small scenario were combined with increasing amount of data/connections.

Appendix B

Qualitative evaluation - session guide

The text, steps and questions used for the qualitative testing. Serving is a guide for each of the evaluation sessions.

Introduction (to tell to the participants)

The conversations will be recorded to produce a transcript. Some quotes and a general summary will be used in my thesis reports.

This system and visualization were intended to provide a proof of concept on how to bring various aspects together to create a complete application. It should bring together: VR, urban data, exploration, real time, interactivity, and collaboration. Lots of research focuses only a few of these aspects. Generally, such research only uses those aspects to research something else, but do so, they must build an application with some of or all these concepts. This is a proof of concept that those things can be brought together in a configurable way so other researchers could use it.

In short, this system uses a configuration file to push input data through a lot of steps to output visualizations. Every step has its own responsibility and either changes the data or creates new data. Every step for every data source can be separately cached to speed up the processing. Which enables the configuration to change during the usage of the visualization.

Some of these use-cases have been prepared to work as proof of concept in this system. We will go through a few steps to showcase these.

Tasks/steps (to walk the participants through)

In a setup with 2 users in an open physical place. Entering VR to see the data virtualization.

1. Get accustomed to the controls and position yourself near the visualization.
2. Look around the visualizations for a bit.
3. Use the button on the wall to switch the data value.
4. Click on a one of the spheres and polygons to inspect some of the data.

5. Look at the pathways and see how the color changes (as I switch it in the web browser)
6. Use the zoom in and out button.
7. Look together at the visualization and try to show something to the other.
8. Use the button on the wall to enable live WiFi data.
9. Have a look at the visualization again.

Out of the VR environment give a quick overview of the rest of the system.

1. Have a look at the management panel in the web browser.
2. Have a look at the configuration and source files.

Questions (to ask the participants after the tasks)

Start a conversation with the participant(s) about the proof of concept application using the following questions.

1. What did you like about it? What not?
2. How did looking together at the same data go?
3. What functionality would make the VR environment significantly better?
4. What do you imagine this could be useful for in the future?

Appendix C

Qualitative evaluation - transcript session 1

Participant 1 (P1) is a PhD candidate at the TU Delft. Working at the faculty of Industrial Design Engineering and is a designer with VR experience.

Conversation and questions were recorded and automatically transcribed with Microsoft Office 365. Resulting transcript was manually cleaned afterwards.

Mirko So what did you like about it or what did you? Didn't you like about?

P1 It so I think from a if I start kind of zoom. Now I like the distinction between changing configurations outside of VR and experiencing it inside of VR like that makes a lot of sense because you don't want to be fretting around with small buttons in VR before you go into it. It does, yeah. I mean it means then the change is a little bit separate, but eventually you could integrate those controls into the VR, but it makes sense of a kind of external non headset dashboard that you can plug into and change things. I like that we could see the same data. I think that's really useful. I'm curious if you're. Imagine this to be a thing that two people who are also in the same physical space. Would use rather than two people who are remote would use. Because for me this makes more sense for. I'm here and someone else is further away and then we can kind of enter a little pocket dimension where we look at just the data. And then I feel present because if I'm in the room with someone, I think VR limits a lot of things, like being able to point at a screen and discuss a little bit more.

Mirko Well, it imagined that this synchronization between pointing at something would be more feasible. Of course, now it was. A little bit in a. Way, yeah, with the ideas, of course, to have that more feasible, because also if someone is further away, you want to point at the same thing. So the idea is. It's also possible. Of course, in the same room. Yeah, and now, well, the limitation, in my opinion is of course that's. We are both in our own sort of space. So where you are physically in the room is different from where you are physically in the not the physical in the physical environment, yeah, push to where I am. So synchronizing that up, if you are in. The same place. Is something that could help this situation.

P1 I'm curious about that because I mean, yeah.

Mirko This of course indeed. But the idea about doing this in the same room is to not have the burden of communication in this proof of concept. Because communication is. And all our Spence.

P1 Yeah, yeah, yeah, I.

Mirko So that would mean you set up for communication through another channel program and it could also be integrated. At the moment, the communication in the same room. It's always easier to.

P1 Yeah, I get that. But I mean I think that would be one of the strengths for the future would be being able to do this remotely. I think it's really nice to be able to cycle through different kind of visualizations. It's also nice to be able to look at the data. From different angles I mean. Of course I've seen like, you know, computer. It's a map. They overlay some dots and then you're done. It gives you a very or like a very two-dimensional take on something. And even though the map isn't really 3D, at least being able to kind of. Walk around it and rotate around it and look at it from an angle. Was really nice. I like that a lot and I yeah, I liked also being able to shift between different sources for the day. I think if you develop that a bit more, I think people who aren't very experienced with the technical setup of data would have a much more kind of naturalistic experience by just putting on a VR headset and looking at it and then. Being able to comprehend what's going on and then. Being able to kind of switch the data sources bit more naturally, I think another well one thing that you would also maybe think about as a as a future thing would be how do I. How do I take a note or record something in the headset so that I can use it later, right? Because if we say like ohh, it's really cool that you know with the live Wi-Fi data we can see over. That, you know, there's a flow from one side to the other. We can say that to each other, but maybe there's a way to add a note that you can then synchronize with the data source. I mean, not something you need to do, but maybe a nice.

Mirko Well, it was actually in in. In sort of the ID. These are in. The parts the life parts thus allow. Another source to be added actually as a sort of annotation source. So because of how it is set up, it should be possible to rather easily integrate like a source that you can also add to well in the environment. Because of the live aspect, this shoot already. If you would make something that adds to the source and make it. Register this life changes. Yeah, then the rest of the system should, as you have seen with the Wi-Fi data, should already process this. And then then you should have another annotation in there. OK, so that's one of the things that should rather easily be possible.

P1 OK. That's something I think would add a lot of value for people using the system. So that's good that that's already on the road map. So to speak. But that's what I liked about it, and a bit of what I. Think could benefit people. Do you have other questions for me?

Mirko Part of the question what do you not like about him is not really a good. Question I think and I. Mean you already said, like in the improvements, or perhaps network, which improve indeed.

P1 And I think one small thing would also be showing the pointer location of someone else would be. Very, very beneficial because. I get the idea of like if you're highlighting this thing then extra information pops up, but I think when you're discussing data points, it's really like I don't know, I would point to things in real life. So I think that would be a thing to add and. Yeah, I think it's a good way to visualize the data in VR and have two people coordinate. So I think from that perspective, I mean make it more stable add to the UI. But I think for a proof of concept is very solid.

Mirko And sort of your details, but how did you how did looking together at the same date as well I think.

P1 So I think it was nice to be able to look at the same data. I think the well, what's challenging for this evaluation is we didn't really have a. Purpose to look at the same data, but that's the evaluation I can imagine. In situations where we actually have a point or like a goal, and then looking at the data can help. Yeah, I think being able to indicate and kind of make a note would be really useful. And but I think having, yeah, having it kind of physicalized in a virtual way. Makes it more. I don't know improves the experience rather than just looking at a flat thing on a screen and then you just go the colors change. Done so, having the 3D nature of it was quite nice.

Mirko And what you're I think you're only interested, but maybe everything else. But what functionality would make this different? Well, better significantly better. Working together, you're all the.

P1 Being able to point being able to take notes. So maybe like a whiteboard feature or like a. I don't know. Yeah, like.

Mirko And the concept of having this table. It was of course a little bit went out of the table, but of course the idea would be to have this circular table and anything that goes out is clipped out. Of course, out of the data that was not really visible now, but. That's the concept. That's what do you think about the concept of? This table you should be able to walk around with people. So I way to look at the data instead of having a for example having a plane map. Of hovering in.

P1 I noticed myself. Going into the map because I wanted to. To zoom in to a part. Without actually zooming in, because then I wouldn't like reduce everyone else's point of. Yeah, because I think that's a thing that you can do with the VR environment is, yeah, is physically. Move closer to a virtual location. So I think in in terms of like a metaphor, having it on a table is really nice. It also brings it up to a better height, and it does. They would help you create boundaries, but then I think you also need to allow people to. Break the boundary and kind of go in.

Mirko Yeah, that's like what you did. Keep allowing that you go in.

P1 So I think that it's a useful metaphor for like. Kind of can contextualizing the amount of space you're actually going to deal with. But then yeah, don't remove the affordance of being able to poke in.

Mirko OK. And last. Question what did? What do you imagine this? Could be useful for in the future. This has worked out with all the things she said.

P1 So I'm thinking I would say largely. Remote interactions I think that would be somewhere where the value would be a little bit higher just because if we're in the same room, you know we can we. Have a similar experience in 3D on a flat screen which is less immersive, but then we can do all the communication stuff without using a thing. So without using pointers and things. So I think maybe remote situations would benefit a little bit more. Definitely I like the urban angle of. As in, it makes a lot of sense to look at spatial data and people. I'm guessing you could also use this both for. Right now, you're kind of proposing this as data analysis. I think you could also use it maybe as like more community engagement. Right. So you have people who live in an area, reflect on how the data is viewed at a larger scale rather than just. You know, show them a photo or show them a thing. You can have it be a little bit more interactive. So I think you could. I think the interactive virtual thing works well for people who are novices with dealing with data. I'm guessing if you're a hardcore urban data person, you probably have a thing that spits out numbers and you're very familiar with the map.

Mirko You might want to have a. Lot more of more.

P1 Yeah, of course. So I think I think situations where you want to be collaborative, but you're limited. So remote and situations where you want to be able to have people easily. Explore the data and not necessarily. We need to do like number crunching, right? Because if you're a complete novice at looking at data, being able to tweak the things is already a little bit strange. But here you have a system where two people can explore data. A third person can act as like a guardian and change the situation problem with questions. Introduce new data sources and so in that way you could very easily bring in like people with less experience of data stuff and have them explore the data and give useful insights. So maybe some kind of community engagement probing things like that.

Appendix D

Qualitative evaluation - transcript session 2

Participant 2 (P2) is a PhD candidate and participant 3 (P3) a master student at the TU Delft. Both working at the faculty of Industrial Design Engineering.

Conversation and questions were recorded and automatically transcribed with Microsoft Office 365. Resulting transcript was manually cleaned afterwards.

Mirko That's the application. That's my proof of concept. So I have just a few questions. What did you like about this and what? Not considering everything I told you.

P2 But I liked that you're. Somehow in it also really like that you can see each other as a. Yeah, the dummy thing, because then you feel somehow that you're doing something together instead of. I also liked the simple thing that you put the buildings as 3D. Objects or not, all of them. I think, but some. Yeah.

Mirko Not all of them, no. It's just an extraction, indeed.

P2 Yeah, because that really helped me to, to interact, to understand where I am because I know that campus area. Maybe a bit better. Because P3 is new to delta, maybe she doesn't know. Yeah, it's harder to understand.

Mirko Might recognize the library.

P2 Yeah, but I think that is really crucial to see. And to understand where you are, yeah.

Mirko So basically to have more. More of these visualization options, which it doesn't don't even really have to tie into the data you would be looking at. Like this, the buildings are also of course a visualization option just on sources that you can decide like now they had no meaning. They had a caller and that was based. I think the caller. I'm not sure what it was based on, but it was based on some some data from that building actually.

P2 Ah, OK yeah.

Mirko But in my example it has had no further meaning.

P2 Now I think it really helped me to understand where.

P3 I liked it a lot, even not really knowing where it was. It's still like it made it seem more real. Yeah. Just like a flat.

Mirko Well, that's good to hear.

P2 And then also when you zoomed in, you were kind of. At some point. Yeah, in. Yeah. Going so low that it feels like you're. Not really standing on the ground, but.

Mirko You can look at.

P2 Almost yes, yeah. And I think for me, when we when I did that, it kind of turned from just the model. That was on the table like a normal, like a maketa or just. Yeah, some.

Mirko Mark her off just a little bit. Of city and.

P2 Into something more realistic, I guess.

Mirko What you could look together at the same data here. Of course, there's not really not hard of. Course to see. To do something together in this example of course. But what would you imagine that? Could be added maybe? To make it even more. To make it look even more together, for example.

P3 What do you mean more together?

Mirko Did it feel like you were together here and could do things together? And was this a setting you might be? And that might be useful for you if you would be looking at some data together and how would that improve your way of looking together or? And other things that would. Should be added to add even more failure to it.

P3 I don't think I can see like what you were pointing at. So I think that would have been helpful. I know you said. That there should be like little kiss and. Again, notice that personally. So that would have been cool.

P2 To be able to like.

P3 Like, I feel like I was kind of exploring. It and like I knew you were. There too, but I. Didn't really like know what you were looking at or like. So just maybe having a better idea. Of OK, yeah.

Mirko A little bit of provider other one is pointing. And if that's what it does added would this make, would it this be very useful to working together? In a way.

P2 Yeah, I think I think we're lacking now a bit of. A context or use case? Yeah, exactly like, because I think this. Is it the data kind of from the COVID? Times where you wanted to have. You wanted to know how many people are aware and how wide the streets are.

Mirko Yeah, that's basically one of them.

P2 Yeah, because then it makes kind of sense what you're looking at. If you know such a context, I think.

P3 Yeah, I was thinking about. Like if I was trying to point out to you. Like one of the. Yeah, little blobs like we would have no way of knowing that. We were looking at the same, yeah.

Mirko Yeah, but if you would have been able to edit point and show where you're pointing then.

P2 Yeah, yeah, exactly. Then you can. Oh, I see a problem here or.

Mirko What you see this?

P2 Trains or yeah.

Mirko We just see this as a useful application for if you work remotely with each other, or also if you are in this setting together.

P3 I think it's a cool. Way like I. I think I see. It more virtually. But also when you're in person and like looking at a model with someone, you're kind of just like both on one computer, like looking at stuff, at least in my experience. So this would be cool, but like you're both kind of like in our own things and able to like see the. Yeah, that makes sense. It's like a little easier to be like collaborating versus.

P2 Yeah, it's a bit more immersive, I think. So, yeah, I think it also really depends on the use case, if it is. Like a very simple visualization. It's also fine, I think on the screen. But if it's getting more, if you can have maybe more different layers of information or more interactivity then. It starts to be more, yeah, more added value.

Mirko Of course, in this case you should imagine that the data is not set, so technically I could change through the configuration with one of showing the whole Netherlands and neighborhoods or heights, and at various other data points in some way like squares with data on top or which just simulate not the square with the. Guys with just a point with some. Data value or. Yeah, like that. It's intended to be configurable.

P2 Yeah, yeah, yeah.

Mirko Is there anything you are really missing? In this environment in this field. At the pointing at least, but. Let's would make it better.

P2 Yeah, I think the most important thing is what P3 mentioned that if you can see what, what the yeah, what the other person is clicking on and the information that pops up when doing that. And then you can really collaborate, because if you cannot, then you are both exploring it, like on your own together instead of really together.

P3 Yeah, I think the only other thing I can think of is like maybe it being like a little bit more realistic. I mean, I bet if I. Have been here for like another month that I would have known where I was and everything. But like I have. No idea which.

Mirko So what do you imagine? This could be useful for? Could it also be useful for your own research? Do you see? Possibilities here to. Show data for your own research, or perhaps you think this is useful for a completely different situation.

P2 Yeah, maybe I'm thinking of because now it was still the data. Still 2 dimensional mostly or you show the. The 3D. Like the circle, the blobs, the spheres. But maybe it could be very useful if you talk about like more. Dynamic 3D models of like shadow or something. Like how shadow moves through the city through the day. Then it makes a bit more sense that you can really have it in in 3D and virtual reality opposed to just like the map on the computer, which is then. A bit harder to put all the information in. Maybe that could be an interesting case. Yeah, not to say that you should do this. I mean, but no, no, no.

Mirko I didn't have. Time for this.

P2 I know, but yeah. So I could see it, yeah. But I think especially when the when something 3D comes into the. Like now the buildings.

P3 Yeah. Yeah. Thinking like heat mapping or like air quality stuff like it would be cool to see, like, the shading like, yeah, just like something like that and more like 3D context. Yeah.

Mirko So about adding a little bit more 3D sources, let's say this could be more useful.

P2 Or the dynamic thing that you had with the changing like 5 seconds interval changing. Maybe we could also be if you need like. Yeah, models where something changed, like traffic or heat.

Mirko Technically it could be added.

P2 Yeah, that is also. Because until then, you'll still feel like you're floating on top of just like a a table. But when you add something dynamic worth reading you.

Mirko It would start to make more sense at some point.

P2 Yeah, exactly, yeah.

Appendix E

Qualitative evaluation - transcript session 3

Participant 4 and 5 are two staff members of the VR Lab at the faculty of Architecture and the Built Environment. They run the VR Lab and are also part of the academic teaching staff. Participant 4 also an assistant professor.

Conversation and questions were recorded and automatically transcribed with Microsoft Office 365. Resulting transcript was manually cleaned afterwards.

Note: the first part of the conversation (before the actual questions), was recorded in Dutch. Some quotes from that part have been used in the Evaluation section and thus were translated. Some parts of the Dutch transcript were cut out because they only contained instructions and general talking.

P4 Ja, Ik ben wel meer dichterbij. Inderdaad, ja, weet je, bij de andere applicaties beweeg je je handen bepaalde manieren kun je zelf in en uitzoomen. Dat is zoals bij RK jongens zo heel fijn, dan hou je namelijk niet de die die die middelvingers In de. Ja de middelvingers die gebruiken. Je ervoor, en dan kun je zelf schalen.

Mirko Ja, hier is dat mogelijk lastiger, want je die deelt de wereld met de ander Natuurlijk. Dat is het voordeel en het nadeel wat betreft schaal.

P4 Dus gemaakt van supermodel, want je bent z'n Tweeën kijkt, en dan kun je dus niet. Op verschillende schalen naar.

Mirko Kijken waar je dus nu kun? Je zou je. Nou, ja, het stukje wat je ziet? Die tekst is Natuurlijk heel duidelijk, eigenlijk zou. Dat Natuurlijk duidelijker moeten dat je ziet waar. De ander naar kijkt. En, Dat is dan het idee dat je ook Samen zou kunnen werken, dus dan zie je ziet het persoons hoofd. Je ziet dan is een pointers uiteindelijk en je ziet waar we naar kijken, dan zou je zeggen, kijk dit.

P4 Een vraagje, je hebt nu aan de huur heb. Je nu oh. Daar ben ik, wat wil ik eruit? Ik kan alweer. Aan, je hebt nu aan? De muur om het te. Om te zetten, maar normaal heb je gewoon een kaart en heb je een legenda bij. Waarom heb je dat niet dat stukje wat je nu aan de muur hebt hangen niet gewoon als een deel op de kaart geprojecteerd. Dat je op de kaarten knopjes hebt van schaal en.

Mirko Dit was op dit moment het makkelijkste. Oké, Dit is helemaal het antwoord. Ja, uiteindelijk, Dit is Omdat het Natuurlijk een proof of concept is. Ooit had ik Natuurlijk. Het idee om dit veel mooier te maken. In praktijk heb je Natuurlijk weer gewoon aan het onderzoeken en heb je In de.

P4 Tijd van nou, dat zou wel een advies zijn om dan inderdaad op de hoek, net als met een kaart een land. Maakt dat je?

Mirko Zou je denken dat? Het ook Als je bijvoorbeeld inzoomt, dan verandert dat. Dus mijn idee origineel was om de controls op de hand te doen.

P4 Het mooie nog op je horloge, hè? De agio dat je gewoon hier kopje bloem hebt, dat je je controles gevoel hebt, gevoel van oh ik. Moet die muur gaan.

Mirko Precies, Dat is, Dat was het originele. Een staande inderdaad is dat. Dat ja in van de logische manieren is, want dan heb je dit Iedereen zijn controles bij.

P4 De hand en, anders Als je het zo doet als dit, zou ik graag willen weten Als ik zeg Zweeds wifi data en wat wat ben ik aan het switchen? Wat zijn de keuzes die ik daar heb? Want Ik heb nu.

Mirko Ja, maar goed, uiteindelijk zou dat Natuurlijk. Het is Natuurlijk weer wederom proefvakantie dat het dat je kan switchen. Ik laat zo buiten de VR wat zien. Wat dan uiteindelijk ook in VR zou kunnen en wat je dan zou zien, is dan per data source dat je kan zien welke velden je hebt en dan kan je gewoon via dropdown op je arm dus selecte. Bijvoorbeeld, wat ja, weet je Laten zien?

P4 Ja, Ik vind het vrij. Abstract nu, ik bedoel we. Weten nu dat het? Een rivier is, Maar ik heb geen idee of dit een bepaalde dag is op een bepaald moment, of welk moment dan. En je zou eigenlijk gewoon dan ja, bij de Switch wifi data eigenlijk een soort scroll willen hebben dat. Je door de tijd kunt scrollen, ja.

P4 Ja de verschillen zijn Natuurlijk heel goed je. Ziet, dan hebben we wel kloppen. Met, Ik heb het gevoel Als ik rondkijk, dan zie je af en toe wat veranderen. Inderdaad, ik zou eigenlijk willen weten waar het meer of groter of kleiner wordt, dus eigenlijk verwacht dat de kleur aangeeft van hé deze groei dat deze krimpt.

Mirko Dat kan dat goed punt, ja.

P5 Ja en Ik ga qua user interfaces Natuurlijk. Dat, ik zeg gewoon heel veel, doe ja.

Mirko Ja, dat heb ik niet aan jullie moeten gaan.

P5 Dat is ook het lastige. Ze nee, maar goed qua proof of concept werkt.

P4 Jaar ook weer? Ja, dat. Is door wat is de meerwaarde? Nu heb je een visualisatie, terwijl Ik denk je het op je scherm te doen zetten naar tweede scherm aan en dan komt het. Daarop dan zie. Ik ook eigenlijk genoeg, voegt nog niet. Heel veel toe om In de VR.

Mirko De VR ja. Nou dat samenwerken deels en het feit dat je. Altijd verschillende soorten data. Kijk, mijn data is Misschien niet om beste proof of concept wat betreft data source.

P4 Wat zou samenwerking zijn voor jou? Wat zou je kunnen doen, wat wil je veranderen, bijvoorbeeld? Of wat wil je dat Mensen kunnen aanpassen?

Mirko Na al deze dingen inderdaad, dus filters de visualisatie types dus kleur maar op sites en op basis van welke voorbeeld is dus ik voel me veel mooier meer dat je inderdaad kan pointen data sheet en dan intuïtie hebt die zeg je nou, Ik wil even dit aanpassen en dan zet dat, bespreek je Samen en dan zeg je, hij past er even aan en dan verandert het. En, dat kan dan tegelijkertijd live data. Ja, verschillende sources zich naar ik doe even die gebouwen uit klik. Klik uit even aan en vergroten.

P4 Ja precies en niet, niet vanuit een soort gids kaart waarbij de data laat zien, maar gewoon veel meer echt ook dat je rondkijken en dan weet je gevoel erbij krijgen van mata schaal en.

Mirko Ja ja het live aspect hier is Natuurlijk. Meer een proof. Of concept, Maar dat bewijs zou ik wel bewijzen dat je hier data van R. DW in kan zetten. Of ja, dat wordt live data van matrixborden heb ik ook naar gekeken, dan zou je uit te zoomen naar Nederlandse schaal. En dan? Hoe druk wegen zijn bijvoorbeeld?

P4 Ja en dan zoom je weer in.

P5 Ja, maar in dat geval, Als je met leeftijden gaan werken, zijn we nog heel erg gaan nadenken van. Waar je die data gaat processen en hoe je.

Mirko Ja, dat zou.

P5 Want dat wil je dus niet zo deze dingen. Allemaal hè, zoals we nu dit modelletje, dat werkt op zich prima, dus dat kan, maar Als je vote gaat.

Mirko Ja tot 100.000 objecten tot 5000. Objecten gaat dat langs zich 300 milliseconden ongeveer.

P4 Kun je goed kijken waar ze met leen push wat binnen je gezichtsveld ligt.

Mirko Ja er kan inderdaad nog heel veel verbeterd worden aan een keuring van het gezichtsveld.

P4 Zo ja, dus je zegt heel Nederland en je kijkt nu Alleen naar. Dit stukje hoeveel Alleen maar dit?

Mirko Ja je zou dan Natuurlijk Als je naar een land kijkt, een heel ander soort TYPE visualisatie bouwen. Je zou dan zeggen, hele andere sources importeren en Switch je gewoon mooi. In ieder geval is dat. Dus tweede ding wat ik laat? Zien is dat er gewoon een?

P4 Verschil beest visualisation ja.

Mirko Een hele configuratie van confier. Dat is eigenlijk wat hierachter draait en in theorie nou, je ziet hier Maar het proces dat de live. Data binnenkomt gaat weer. Door dingen heen. Je zou Natuurlijk de hele configuratie file zou ook op je arm zullen switchen en dan zeggen. We Switch en dan heb je in 1 keer 1 hele andere visualisatie die je hebt gebouwd, al een andere keer wordt ingeladen dan.

P4 Nou, Ik kan me voorstellen dat het. Een leuk voorbeeld hiervan. Is ook Als je binnen de TU wijk bezig bent van ja, hoe oud is ze? Gebouwen zijn welk bouwjaar is het of hoeveel Energy gebruikt het gebouw? Dat je dat soort data gewoon kunt visualiseren Als je rondloopt In de natuur werkt, zodat ik geweldig. Zijn Als je een keer?

Mirko Één van die ideeën ook hier. Andere ideeën hierin waren Natuurlijk deel 4 van een live data. Dat dit werkt, betekent. Ook dat je. De andere kant op kan werken door iets te pointen, zou je kunnen maken en daarmee een file updaten met een annotatie die je in geinplein via VR en om dat dus de live deel werkt. Dat betekent dat enige wat je hoeft te doen is te maken dat hij de val wordt aangepast. En dan werkt het, dus dan ziet Iedereen jouw annotatie verschijnen op schermen bijvoorbeeld.

P4 Belletje en iets en het voordeel is dat je principe hier kunt zitten achter je bureau en de hele theebar kunt doorlopen op ooghoogte perspectief en of er doorheen kunt vliegen en bij alle gebouwen aan het Naties kunt maken over bijvoorbeeld huidige energieverbruik of huidige bezetting. Of noem maar op. Ik weet niet hoe gedetailleerd je de data hebt, maar.

Mirko Dat ja dat ligt. Dat is dus niet, dat ligt aan de persoon hier. Want Ik kan SHAPE valse en Georges aan om te eigenlijk.

P4 Net ook een sensoren je hebt en welke data je je doorvoert.

Mirko Dat zou je dan allemaal moeten kunnen configureren. De tafel twee keer je hebt, je wilt van. Dezelfde data 3. Keer iets tarief verschillende versies Laten zien van 3 sources toen van dezelfde data. En dan heb je?

P4 Scheers In de temperatuur kijken kun je de temperatuurverschillen zien. In elke ruimte kunt uitmeten. En dergelijke, nou, Dat is. Ik heb nu net een.

P5 Dus net afgestudeerd van onze eergisteren? Die jongen die. Met face changing Materials in gevels en dat realtime wilde visualiseren. Helemaal toegekomen aan het Unity gedeelte. Maar ja, zelfde ideeën inderdaad.

P4 Dus het zou Natuurlijk geweldig zijn Als je beheren van dit gebouw gewoon. Versie wordt gebouw loopt en gewoon per ruimte kunt zien wat de temperatuur is en waar ik verbeeld boven de boven de 30 is. Die zegt Van hé.

Mirko Maar hier gaat iets mis. Ja, zoiets zou. Je kunnen door gebruiken. Inderdaad door source van een een groot inderdaad de. Objecten te sturen. En dan binnen daar weer al deze punten. Bijvoorbeeld, ja, dat zou wel, het zou geweldig zijn. Ja een van de ideeën was.

Mirko Om dat dit dat je een soort van streetview kan toevoegen en Als je op deze schaal en kan je net als dat je Point op een stukje van de kaart en dat je dan in je In het ruimteveer zitten, dus je hebt die tafel en de omheen dat je omheen de streetview ziet van. Dat punt waar je naar? Ja, Dat is onder andere waar om dit concept op gekozen met tafel om met je Samen bent. En dan zou je In de pointen zijn, gewoon tussen de immers hier van de streetview die we zien en dan heel snel kunnen inspecteren van waar? Wat wat? Hoe ja br.

P4 Maar wel het materiaal allemaal hebben en een goede locatie gezet. Maar goed, Dat is.

P4 Maar dat moet mogelijk zijn. Hoe heb je dit?

P5 Project nu in C# opgezet zijn dat eigenlijk per geojson shape, een soort van module aparte bibliotheek dat je met een soort van plug ins. Structuur kan werken. Of is het? Nu nog meer een soort van monoliet geheel. Ja nee maar. Ik bedoel, zeg maar meer gewoon de de opzet van je soort project. Is het gewoon een groot script waar je al deze dingen in hebt geleend of hebt opgebouwd of heb je een structuur opgezet waarbij je eigenlijk per. Want Jason is een heel ander formaat dan een shapefile geloof, ja.

Mirko Er zijn verschillende manieren inderdaad. Het is nu een klein beetje, soms Natuurlijk een rotzooi hebben. Uiteindelijk van de vals zijn gestructureerd, maar uiteindelijk zou er gewoon per data die binnenkomt, leest die inderdaad data uit en per future set is het eigenlijk een geojson Natuurlijk. Maakt die een object aan waar die In de greeuw een geojson render aanmaakt, aanhangt in Unity automatisch en dan krijg je dan handelt die het renderen van dat stukje. Future set af oké.

Mirko So what do you like about it? The system itself, what do you or what don't you like using the general concept?

P4 I like that you can quickly visualize data. And I think that's an important future feature. So we're also discussing with pre. Yeah. Like I said. Like we have buildings here. It would be great if we have a data set. There are so many data sets and if you can maybe already show data from buildings like not just the map with the age of the buildings or the construction but you. Put this on your head and that you show things how they are. So that's one thing. And second thing I what I like is that you do live data, so that could be any sensor like temperature. Indeed, amount of people in the room. Amount of people in the room etc. So I think that that's a pro and the good thing is you can do it from your desk because it's a virtual model. So you can really you have an idea where you're going. And I think for a lot of people, it will. It's difficult to do it with a map if we're here in this building and we are going to discuss the. Hola how temperatures in the aula then, people have no idea what they're talking about, so that's nice if you can relate the data with the place. And of course, what? Like you said, the visualization can be stronger and how you have the user interface. The the kind of options to kind of control, so it's kind of it's kind of abstract now, but I think that can be much stronger but you know already said that this is a proof of concept. So it's great that there's a proof that you. Can do data. But yeah, improving the controls and. Having grip on what you're showing it would be.

P5 Well, I agree with, say, from the live data, it's the interesting thing. Just wondering if you looked at other applications in this direction like RTO or other our few others I think. They might give you some ideas what you can do or what your application is going to do differently, but yeah, definitely the live data is nice.

P4 And if you want to continue this, I think you need to interdisciplinary team. So for the mapping the the ground floor mapping to understand how people read maps, the visualization of the data itself, the kind of menus for their user interface. So I think you need a. Lot of people. Being involved to help you out with that and then you can make the backbone of the system. And think about use cases that you don't. I mean the better the use case then there might be a need for implementation and that. Also forces to. To update and work on it. I mean it, it will be pity if you have done it. It's your thesis and. You put it in a book and you have a couple of screened ups and. Yeah, so so many times. People make beautiful databases systems. Etcetera, and then it ends up decision system. For example, they all end up in booklets and they have me run once and only the person who did it as a tease is nose and after that. It's nice, but so you think about that. So I think there are many cases, especially about the occupation of the building that were done and that are running at the moment. So students can find workspaces based on. The connections, etcetera. So really think about the use cases, how it could help.

Mirko OK. And the coloration parts that you know about that it's useful? Considering you would better see what the other is doing like you see the pointer and you can point for example you put.

P5 Well, I'm not sure if I could see where you were pointing at.

Mirko You couldn't see yet. She only the text. But let's say I would improve the synchronization you need and you really see also the laser beam from the order. If they actually say wait, it should change the color.

P5 If you are with two people, then that's OK, but if you're with more people then I. Wouldn't want to. See all the laser beams because then probably you cannot see what you're pointing at.

Mirko You could make it only if you trigger that you see your beam, so points.

P4 I think it's nice if people talk that they can really indicate and talking about this object. So they can. Really point at it and then it. So it will be good. You have Lucas Archeo as well. How it works there because there you have. I only have. I have a feeling in this case that. You decide on the legend of the. Map the third. The in this case it's not a map, it's 3D model. But you decide on the on the legend of it, but I don't have the feeling that that, that you're collaborating for.

P5 Now it's just sharing and discussing data and collaboration.

P4 So the nice thing could be that why do this is you're at different place in the. And from different locations you are in the same model. That will be the future help for it and that has been done before. So we the archaeo thing can do it worldwide, we are ago is a year ago is a fee our environment which runs that. So there are examples of it how it can be done. And that's really nice. So if archeo, if I'm throwing up, I can join a project with one of my students and he or she can lead me through the Tudelft campus area and indicating what he. Or she has changed in public. Space or in buildings. So and then you see what people are looking. At that, people are pointing at and together kind. Of for reshape things there. So that's the kind of collaboration we are used to. What so, so we probably a bit advanced already there.

P4 So in that sense, the collaboration could be discussing something together and and really make sure that we did that. You're discussing the same object, the same, the same entity.

P5 Yeah, I agree. So right now it's just more inspecting data then it's collaboration on data.

Mirko Yeah, there's still forced the. Board use case in this case. That would improve the. Data than there that could make more. More, for example, assignments to figure something out in the data, and then you have more sense of use case for.

P4 Yeah, well, what could be a thing is that you have to, let's say you have a building size, you have the temperature of rooms, the. The facility manager is inspecting the building. He doesn't have to walk through it to read out the temperature. He sees that there is a room which is overheating, he could say, and that in a scenario he or she switches on a device or the device is implemented to cool it down and see what the effect is. Then there is a collaboration. Maybe there's a discussion and there is also intervention. And it could be something with. This real need there. Like here there's a ventilation system. It's switched on because it's they see it or it's like a test for future improvement of the room. Because it's necessary and based on, let's say people are using the room at times. When it's overheated. I mean, that's. That's if the room is not used when it's overheated, then it doesn't make sense to invest in it.

Mirko OK. And I think you also already pointed out what this could be useful for in the future? I think you say what you said. There was the life aspect mostly about this.

P4 Well, it's two things. I think it's also good to inspect. What is there? We have so much data which is in 2D, which is hidden in maps, so making it visible in the 3D World is really helpful. Also for students to see something about let's. Say the material, the building, the age of. A building energy efficiency. But also the live data there and but then doing something with it is in its. Next phase probably, yeah, yeah.

Mirko Yeah, I hope to prove that it's possible to please bring these things together, but you've seen the configuration. And that should be easy to switch and change things. After of course of improvements, but.

P4 Yeah, but you have to see what is the. Main line for your project.

P5 I think if you're dealing with live data, then collaboration might be difficult because, for example, the highway we are discussing. If you want to, for example, change the highway from three links to four lanes, then the live data is. Because anymore, because things are starting to do a simulation, and that's, I think, a step further.

P4 But that's to be a future.

Mirko And the live data I think proves that it could also be a model. Of course of data.

P5 But then you have still a back end behind it, doing all the calculations and simulations.

Mirko You would probably link. To this and this application will be separate from. The model then you. Link the model as in live data and. I would have to make something that's controls. That you can. Yeah, make a control and you're a fighter. That's tearstone will. That outputs to the data. Holder case. Of course, yeah.

P4 Yeah, but that would be nice as well. So that's another path to go, not for your project, but for future path to have. Look at the scenarios and you can say the highway. Let's take the A13. There's congestion at certain times and then you. Change the number of lanes or you change the the the traffic lights the excess. Lights and then. With your interference, and you can immediately see the effect on traffic for and based on that you can make decisions so you can make. A decision to not. Only observation tool but also decision tool. So there are different. Things you can learn from it. You can observe, learn but also. At the end, do interventions to.

Mirko Yeah, and this, this will be done the framework to. Do that for people.

P4 Yeah, yeah, yeah. But that would be nice because we see lots of applications now, like typing engine. It's nice for the Environmental Act, new environmental law. So you can test. New buildings in it, we have a plot and you want to. Make a building there. Then you have to see what the effect is on the neighboring buildings. And usually people do that by that by themselves. In the 3D but what? How would it be if you use this kind of tool to also see the effect and that different people can discuss different interventions there instead of one person running it and doing the different tests? So yeah, I see opportunities, but far, far away dot on the horizon, how could integrate with other environments?

Mirko Well, that's a good model at least. My goal is reached, yeah. Well, thank you. And I think this is OK.

P4 Nice for showing. Well, very nice.

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