MASTERARBEIT / MASTER’S THESIS

Titel der Masterarbeit / Title of the Master‘s Thesis

„Web-based 3D visualisation of 3D air temperature data in a 3D city model – Evaluation of different visualisation approaches.“

verfasst von / submitted by

Sebastian Alexander Eder BSc

angestrebter akademischer Grad / in partial fulfilment of the requirements for the degree of

Master of Science (MSc)

Wien, 2021 / Vienna 2021

Studienkennzahl lt. Studienblatt / degree programme code as it appears on the student record sheet:	A 066 856
Studienrichtung lt. Studienblatt / degree programme as it appears on the student record sheet:	Kartographie und Geoinformation
Betreut von / Supervisor:	Ass.-Prof. Mag. Dr. Andreas Riedl

Sebastian Alexander Eder: *Web-based 3D visualisation of 3D air temperature data in a 3D city model - Evaluation of different visualisation approaches.* (2021)

The work in this thesis was made in the:

Cartography and Geoinformation
Department of Geography and Regional Research
Faculty of Earth Science, Geography and Astronomy
University of Vienna

Supervisors: Prof.Dr. Andreas Riedl

ABSTRACT

This master thesis is dealing with 3D air temperature visualisation in 3D city models, in the research field of 3D geovisualisation.

Due to the predicted growth of cities and urban areas, and due to the effects of climate change on the urban climate, issues around urban climate are increasingly becoming the focus of urban planning, participation processes and political decisions. For this reason, there is an increasing demand for improved analysis and visualisation of air temperature data within cities, for example, to better map urban climate phenomena (e. g. urban heat islands).

As a digital tool for the analysis and visualisation of spatial data, 3D city models are used in urban planning. Current examples of 3D city models focus on visibility, solar potential or energy demand analysis, noise propagation analysis, shadow flicker and air pollution visualization, among others. In contrast, implementation examples dealing with the visualisation of 3D air temperature data are not yet known. Also, the practical implementation of i. e. a regional climate model in a 3D city model has not yet been described in literature. As a consequence, there is no related work dealing with the question of how implemented visualisation approaches (VAs) perform in terms of usability.

In the scope of this master thesis, potential VAs are identified by a comprehensive literature review. A continuous 3D air temperature data set of a regional climate model is preprocessed and implemented in the 3D city model of Vienna by means of a heuristic approach. In sum three potential VAs, namely a 'point cloud' approach, a 'cross section' approach and an 'isosurface' approach are applied. ArcGIS Pro and CesiumIon are used as visualisation pipeline. The visualisations are shared as 3D web scene. Finally, the usability of the implemented VAs is evaluated by three experts from the field of 3D geovisualisation and usability inspection by means of a heuristic evaluation.

Based on the practical implementation of three VAs, three workflows on how to visualise 3D air temperature data in the 3D city model have been drained. The thesis shows that all three VAs chosen are suited to implement 3D air temperature data into a 3D city model and to visualise the data. However, the results of the heuristic evaluation reveal several usability problems of the implemented VAs: VA_1 shows 19 usability problems with an average severity rating of 1.95, VA_2 shows five usability problems with an average severity rating of 1.67 and VA_3 shows four usability problems with an average severity rating of 2.42. The evaluation leads to the conclusion, that VA_2 is best suited to visualise 3D air temperature data within a 3D city model, based on given data and selected visualisation approaches.

ZUSAMMENFASSUNG

Diese Masterarbeit beschäftigt sich mit der 3D-Lufttemperaturdatenvisualisierung in 3D-Stadtmodellen, im Forschungsbereich der 3D-Geovisualisierung.

Aufgrund des prognosizierten Wachstums urbaner Ballungräume und den Auswirkungen des Klimawandels auf das Stadtklima, rücken stadtklimatechnische Fragestellungen vermehrt in den Fokus von Stadtplanung, Partizipationsprozessen und von politischen Entscheidungen. Aus diesem Grund steigt auch der Bedarf nach einer verbesserten Analyse und Visualisierung von Lufttemperaturdaten innerhalb von Städten, um beispielsweise stadtklimatische Phänomäne (z.B. Hitzeinseln) besser abbilden zu können.

Als digitales Hilfsmittel zur Analyse und Visualisierung räumlicher Daten kommen in der Stadtplanung 3-dimensional (3D)-Stadtmodelle zum Einsatz. Aktuelle Anwendungsbeispiele von 3D-Stadtmodellen konzentrieren sich u.a. auf Sichtbarkeits-, Solarpotenzial- oder Energiebedarfsanalysen, der Analyse von Lärmausbreitung, von Schattenwurf und der Visualisierung von Luftverschmutzung. Anwendungsbeispiele, die sich mit der Visualisierung von 3D-Lufttemperaturdaten befassen, sind dagegen nicht bekannt. So ist auch die praktische Implementierung eines regionalen Klimamodells in ein 3D-Stadtmodell in der Literatur noch nicht beschrieben worden. Weiters sind keine wissenschaftlichen Studien bekannt, die sich mit der Frage befassen, wie implementierte Visualisierungsansätze (VAs) hinsichtlich deren Benutzerfreundlichkeit abschneiden.

Im Rahmen dieser Masterarbeit werden potentielle VAs mittels einer umfassenden Literaturrechereche identifiziert und beschrieben. In Folge wird ein kontinuierlicher 3D-Lufttemperaturdatensatz eines regionalen Klimamodells aufbereitet und über einen heuristischen Ansatz in das 3D-Stadtmodell von Wien implementiert. Die Visualisierung von drei unterschiedlichen VAs, nämlich eines 'Point-cloud' Ansatz, eines 'Cross section' Ansatz sowie eines 'Isosurface' Ansatz, erfolgt mittels ArcGIS Pro und CesiumIon und wird als Web-Szene freigegeben. Die Benutzerfreundlichkeit der implementierten VAs wird abschließend von drei Experten aus dem Bereich der 3D-Geovisualisierung und Usability-Inspection mittels einer Heuristischen Evaluierung bewertet.

Basierend auf der praktischen Implementierung der drei VAs werden drei Workflows abgeleitet, die die Visualisierung von 3D-Lufttemperaturdaten im 3D-Stadtmodell beschreiben. Die Arbeit zeigt, dass jeder der drei gewählten VAs geeignet ist, 3D-Lufttemperaturdaten in ein 3D-Stadtmodell zu implementieren und in diesem zu visualisieren. Die Ergebnisse der heuristischen Evaluation machen deutlich, dass jeder der VAs mit Anwendungsproblemen verbunden ist: So weist VA_1 19 Anwendungsprobleme mit einem durchschnittlichen Schweregrad von 1,95 auf. VA_2 zeigt fünf Anwendungsprobleme mit einem durchschnittlichen Schweregrad von 1,67 und für VA_3 werden vier Anwendungsprobleme mit einem durchschnittlichen Schweregrad von 2,42 beschrieben. Die Auswertung führt zu dem Schluss, dass, basierend auf den gegebenen Daten und den gewählten Visualisierungsansätzen, VA_2 am besten geeignet ist, um 3D-Lufttemperaturdaten innerhalb eines 3D-Stadtmodells darzustellen.

ACKNOWLEDGEMENTS

In this section I want to thank the people which supported and guided me during the development of my master thesis.

First of all I want to thank my supervisor *Andreas Riedl* for delivering the topic and for the guidance and valuable suggestions during the conduction of this master thesis.

I want to thank *Hubert Lehner* for the interest in my research question, the participation in several meetings, for providing the data of the 3D city model and for acquainting me with key figures in the field of urban climatology. I also want to thank *Tanja Tötzer* and *Johann Züger* for the opportunity to work in the competence unit 'Digital Resilient Cities' of the AIT, for their patience and for the technical support and countless hours of explaining basics of numeric modelling and LINUX. Further I wish to thank the participants of the heuristic evaluation *Florian Hruby*, *Dennis Edler* and *Stefan Trometer*, who allowed me to evaluate the applied approaches and to complete my master thesis. Based on their detailed evaluation and findings, the applied visualisation approaches can be further developed.

I want to thank my Cartography and Geoinformation *colleagues* for exemplifying how to conduct a master thesis and how to not give up. My gratitude also goes to the CTL of the University of Vienna which supported me to structure my thesis and improve my writing techniques.

Finally I want to thank my *friends*, especially my companion *Lena* for their continuous support, the proofreading and patience during the time of developing and writing my thesis. Last but not least: Thanks *Jör*g for the idea, it was fun.

INHALTSVERZEICHNIS

ABBILDUNGSVERZEICHNIS

TABELLENVERZEICHNIS

ACRONYMS

1 INTRODUCTION

1.1 MOTIVATION AND PROBLEM STATEMENT

In 2018, 55% of the world's population have been residing in urban areas. Based on forecasts by 2050 this number will increase to 68% [132]. The United Nations, Department of Economic and Social Affairs, Population Division [132, p.2] states

> 'Globally, more people live in urban areas than in rural areas, with 55% of the world's population residing in urban areas in 2018. [...] and by 2050, 68% of the world's population is projected to be urban.'

This process is also driven and aggravated by population growth, which will put significant pressure on cities. The *World Population Prospects: The 2015 Revision, Key Findings and Advance Tables*-report published by the United Nations, Department of Economic and Social Affairs, Population Division [131, p.2] points out that:

> '[...] the world population is projected to increase by more than one billion people within the next 15 years, reaching 8.5 billion in 2030, and to increase further to 9.7 billion in 2050 and 11.2 billion by 2100.'

According to the Intergovernmental Panel on Climate Change (IPCC) — *Special Report* 1.5°C of 2018 [58] the average global surface temperature rose approximately by 1°C above pre-industrial levels caused by human activities. Between 2030 and 2052 global warming is likely to reach 1.5°C. This scenario will have a huge impact on the inhabitants of cities all over the world and will affect human health with primarily negative consequences [58]. Patz et al. [104] indicates two major climatic effects on the health of city dwellers: 'First a heat- related morbidity and mortality [...]', and secondly '[...] a climate-mediated change in the incidence of infectious disease.' [104, p.315].

The estimated population growth, the relocation to the cities, the predicted increase in the number of heat days and temperature as well as the associated physical strains on the inhabitants pose enormous challenges for political decision-makers, urban planners and the civil society [48, 81, 114, 115].

In order to approach these challenges, decision makers, administration, city planers and other participants are already trying to implement adapted urban planning measures [70], intensifying research [115] and supporting the further development of existing instruments [101], like spatial tools and technologies for enabling better decision making [130]. As regards the latter, according to Batty [6] there is a particular need to develop the traditional 2D approach for visualizing and analysing future city scenarios. As a result, in recent years, more and more 3D visualisation and analysis tools have been developed and implemented to support decision-making processes and monitoring. These visualisation tools — e. g. 3D city models — also facilitate participation processes.

Although there has been progress in the area of 3D city models in recent years, Stahre Wästberg et al. [125] points out that the need to visualize data is still huge, when it comes to environmental issues and the purpose of supporting urban planning. Especially in the field of invisible 'air-data', such as air pollution, temperature and noise, 3D-media needs to be further developed [125].

In 3D-media, air pollution or noise are often visualized by using coloured sphere positioned on a surface [85], horizontal polygon layers [125], 3D observation points or contour lines [65] (see Chapter 3). A pilot study by Stahre Wästberg et al. [125], for example, presents vertical and horizontal layers as well as point clouds as a conceptual approach. However, this unfinished study focuses on the visualisation of air pollution and not on temperature. Beside the fact that temperature data in the range of 'air-data' visualisation plays a subordinate role, urban climate scenarios often represent neighbourhoods or small districts. This is partly due to limited technical resources.

This master theses will approach the knowledge gap of the visualisation of 3D air temperature data.

1.2 RESEARCH OBJECTIVES AND QUESTIONS

The overall goal of this master thesis is to enrich a 3D city model with temperature data, describe the workflow and apply a stakeholder evaluation to evaluate and discuss method and result. The results of this thesis are expected to support the further development of 3D city models, approach the knowledge gap of the visualisation of 'air-data' and propose solutions for emerging issues.

The main research question of the master thesis reads as follows:

How can 3-dimensional air temperature data be visualized within a 3D city model and how do implemented visualisation approaches perform in terms of usability?

In order to answer the research question, following sub-questions need to be addressed:

1. What are potential 3D visualisation approaches to visualise 3D air temperature data?
2. What are main work steps to visualise 3D air temperature data within a 3D city model?
3. Which evaluation method is suitable to evaluate the usability of the applied VAs?
4. Which set of heuristics is appropriate to conduct a heuristic evaluation of the applied VAs?

1.3 CONTRIBUTION

The master thesis contributes to the field of '3D visualisation of 3D air temperature data within 3D city models'. It describes concepts of potential 3D air data visualisation approaches, provides workflows of the implementation of 3D air temperature data in the 3D city model of Vienna and detects potential limitations of the current available data sets. Findings of the subsequent evaluation process shall indicate, which implemented visualisation approach is best suited regarding their usability. These findings are expected to contribute to the improvement of 3D geovisualisation of 3D air temperature data within 3D city models and in further consequence to maintain urban climatology research, urban planning and public participation processes. As a further consequence—beneath the identification of limitations of the applied visualisation approaches—findings can contribute and manifest the public value of 3D data in general[54].

Moreover, the master thesis contributes to the goals of the 'Smart City Wien - Rahmenstragie' [70] of rolling out Open Government Data (OGD) and supports the visualisation of a relevant topic.

1.4 THESIS OUTLINE

To answer the research and the sub-questions this master thesis is structured as follow:

Chapter 2—Theoretical background—deals on the theoretical background for this thesis, particularly in the fields of urban climatology, 3D city models, geo-visualisation and the evaluation of visualisation approaches.

Chapter 3—Related work—outlines related work dealing with potential *visualisation approaches VAs* and *visualisation applications*, which allow to visualise air data within 3D city models. From the key findings, a conclusion is drawn which VA is suited to be practically implemented in the scope of this master thesis. Based on related work guidelines how to implement air temperature data in a 3D city model are drained.

Chapter 4—Methodological approach—gives an overview about the methodological steps applied in this master thesis and their contribution to answering the research question and the subquestions. This chapter also describes the case study area regarding its statistical key indicators, climate conditions or the state of the are of the 3D city model provided by the urban administration.

Chapter 5—Visualisation of 3D air temperature data—describes the implementation of three different visualisation approaches (VAs) in the 3D city model of Vienna. The focus lies on the documentation of applied GIS methods, tools, data sets as well as preprocessing steps and the data visualisation in the visualisation applications.

Chapter 6—Evaluation of the visualisation approach— documents the implementation of the evaluation of the applied VAs by describing the used methods, the conduction of the HE and listing the results of the evaluation process in detail.

Chapter 7—Discussion and Conclusion—finally answers the research questions and the corresponding subquestions. The results were interpreted and the used methods discussed. This chapter also gives an outlook for further research to be done.

In addition to the described chapters following appendixes were attached:

Appendix A shows the provided guideline used for the expert interview of the evaluation process.

Appendix B shows generalized workflows of the implementation process of VA_1, VA_2 and VA_3.

2 THEORETICAL BACKGROUND

This chapter details on the theoretical background for this thesis, particularly in the fields of urban climatology and climate models, 3D city models, 3D geovisualisation and in the evaluation of visualisation approaches. Also the chapter, in the section about 3D city models, describes the theoretical background behind use cases (UCs), application domains, spatial operations, LOD of 3D city models and the data format CityGML in detail.

All these sections describes GIS elements, therefore the term GIS is explained and defined in the following lines. The term Geographical Information System (GIS) was invented in the 1960s [13, 127] and can be defined—in a 'narrow' sense—as a computer-based system that provides the capabilities of (1) *data capture and preparation*; (2) *data management*; (3) *data manipulation and analysis* and (4) *data presentation* to handle *georeferenced data* [56]. In a 'wider' sense a GIS additionally require *hardware*, *software* and *users* (see: Chapter 5). The main task of a GIS is to derive new information from existing georeferenced data. GIS differs from other information systems by the common processing of geometry, topology, time and attribute data [13].

Geographic Information Science (GIScience) is the scientific field that deals with the aspects of geoinformation and the handling of spatial data [47, 56]. Related terms for geoinformation include *spatial information* and *geographic information* [13].

2.1 URBAN CLIMATOLOGY AND CLIMATE MODELS

According to Arnfield [4], urban climatology describes climatic processes relating to *urban atmospheric turbulences*, *exchange processes for water and energy* or *temperature fields of cities*. It allows e. g. the identification of areas of risk, the evaluation of mitigation approaches to lower the surface temperature or the detection of Urban Heat Island (UHI)[1] [87]. The identification and description of climate processes take place on different *levels of climatic scale* and within different *layers* (see Figure 2.1).

Oke [102] classifies the scale levels into the categories *mesoscale*, *local-scale* and *microscale*. Mirzaei [87] adds to this classification the category *building-scale* (see: Section 2.1.1).

The distinction between the Urban Canopy Layer (UCL) and the Urban Boundary Layer (UBL), which impact urban climate, is essential to the issue of scale and a guiding principle in urban climate research. The UCL reaches from ground to roof level. It contains processes of airflow and energy exchange. The UBL, starts above roof level and is directly affected by the presence of the urban surface. This layer is a part of the Planetary Boundary Layer (PBL), the lowest part of the atmosphere [4].

Although progress has been made over the last four decades, urban climatology is still required to come to terms with heterogeneity and complexity. Research still has to decide between detailed mapping of urban morphology or in interpreting observations at aggregated scale [4, 87, 114]. As spatial scale increases, spatial variability is likely to be reduced [1].

1 The UHI is an urban area which is significantly warmer than its surrounding rural area. It is a special feature of urban climate and varies due to daytime and intensity of wind. UHI reduces the habitats' comfort, elevates the energy demand of building and increases the heat-related mortality [87]. According to Arnfield [4], UHIs are the most well documented example of anthropogenic climate modification.

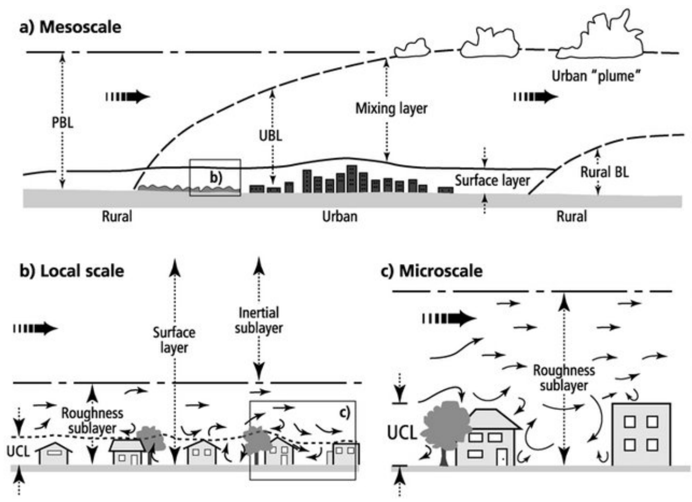


Abbildung 2.1: Climatic scales and vertical layers of urban areas [102].

Urban planning and development are meanwhile influenced by findings of urban climatology. According to the IPCC [58], any increase in global warming will have negative consequences on the urban climate. The impact of heat waves, e. g. can be enhanced by the UHI effect. Available *adoption options* are, beneath others, green infrastructure, sustainable water management, sustainable land use and planning, the increasing of the albedo of cities, or house and roof greening [58, 72, 113].

The *data sets* used in urban climatology are provided from the field of remote sensing (e. g. satellite thermal imagery), measurement stations and urban climate models [4, 87, 115].

2.1.1 Urban climate models

Urban Climate models are used to describe climate processes and allow climatic projections in cities. Urban climate models are modelled based on datasets provided from mobile measurement stations, local weather stations and satellite thermal imagery and differ with regard to scaling, resolution and methodology [87, 114].

According to Mirzaei [87], urban climate models differ in terms of scale first and foremost because of differences in purpose (see Figure 2.1). *Building-scale models* or Building Energy Model (BEM) are limited to isolated building envelopes. Outdoor parameters such as temperature, moisture, solar- and long-wave radiation are external inputs. These models are developed to investigate the impact of future scenarios of climate change on the building envelope. As examples for BEM-tools `EnergyPlus`, `ESP-r` and `TRNSYS` can be listed [87].

Microscale models or Microclimate Models (MCM) focus on the interaction of a building with its surrounding environment. These models can be extended by solar radiation and surface convection from the buildings' surfaces. The MCMs allow the investigation of the impact of parameters such as street canyon aspect ratio, surface materials, vegetation and surface convection, building orientation, pedestrian comfort and urban ventilation. These models show a spatial resolution of a few meters. A weakness of MCMs is their limited domain size of few hundred meters [87]. As examples for micro-scale models, `ENVI-met` or `MUKLIMO_3` can be named [106, 81, 145]. Science and academia is investing huge efforts in extending micro scale models to the domain size of entire urban areas. As example, the German research framework 'Urban Climate Under Change - [UC]²' can be mentioned [48, 81, 114, 115].

Cityscale models are working on a mesoscale level. These models analyse the impact of urban-scale policies (e. g. urban ventilation, greening, pollution dispersion management) and are adopted in urban climatology and meteorology fields. They are based on equations of fluid dynamics and integrate soil, cloud cover and radiation into calculations. A major weakness of mesoscale models are a low resolution of the surface layer [87]. As example for city-scale models the COnsortium for Small scale MOdelling - model in CLimate Mode (COSMO-CLM) can be named.

2.1.2 Urban climatology in research

Mirzaei [87] summarized the research interests of urban climatology into six major categories. The first category—*Urban ventilation and surface material alteration*—deals with the impact of material and surface change of e. g. a buildings' skin on the urban climate. In the second category—*health and comfort*—the impact of the UHIs on pedestrians' comfort and the evaluation of mitigation strategies to lower the heat related mortality rate is investigated. Climate models are also used to explore the variation of the location of UHIs within a city and time of day. These studies are summarized in category three—*UHI spatial-temporal variation*. The category four—*model evaluation and enhancement*—describes the integration of different types of models into multiscale models to cover the existing limitations or weaknesses. Category five—*future temperature forecast*—allows the prediction of UHI impact on future outdoor and indoor air temperature. These studies help to adapt new strategies and policies in the field of urban development. Category six—*building energy saving*—describes the impact of UHI or climate change on the cooling/heating demand of buildings [87].

2.1.3 Data Format - Network Common Data Form (NetCDF)

A typical data format used in climate research is Network Common Data Form (netCDF) (.nc). Further data formats are Hierarchical Data Format (HDF) and GRIB [92].

The netCDF is a set of machine-independent binary formats and software libraries. It supports the creation, access and sharing of array-oriented scientific data and can be seen as a community standard. The University Corporation for Atmospheric Research [133] describes data in netCDF format as: self-describing, portable, scalable, appendable, shareable and archivable [133]. The data format is commonly used in oceanography, meteorology and climatology applications. Every file has a 'header' which describes the data arrays and arbitrary file metadata in form of name or value attributes. The data format was invented in 1989. In August 2019 the netCDF - C library version 4.7.1. and in September 2019 the netCDF - Fortran library version 4.5.1. were published. In version 4.0, the HDF 5 was introduced. It allows to create larger files and multiple unlimited dimension. netCDF programming interfaces for the languages C, Java, Fortran, Python, IDL, MATLAB, R, C++, Ruby and Perl were supported and maintained by the Unidata program Center.

2.2 3D CITY MODELS

In this master thesis the term *3D city models* always refers to 'virtual' or 'digital' 3D city models or 'digital twins'.

Biljecki et al. [12] defines 3D city models as a ...

> '[...] representation of an urban environment with a three-dimensional geometry of common urban objects and structures, with buildings as most prominent feature.' [12, p.2843]

Based on technical innovations and new data survey methods in the last 20 years 3D models of entire cities (see Figure 2.2) were developed, constantly advanced and browser-based visualised [12].

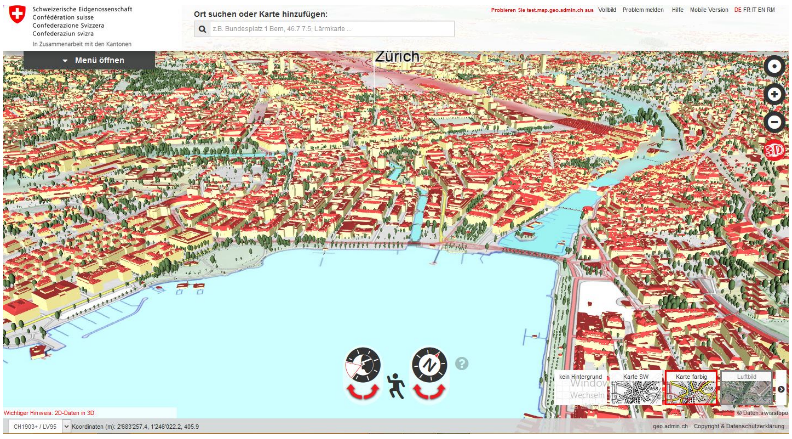


Abbildung 2.2: 3D city model of Zürich in 2019 [16].

2.2.1 Use cases, application domains and spatial operations

Batty et al. [7]s' conceptual study on the use of 3D city models shows a focus on visualisation and spatial planning *use cases (UC)*. UCs can be defined as a ...

> '[...] meaningful set of spatial operations that accomplish a goal a user wants to achieve with a spatial data set'. [12, p.2846]

As typical UC of 3D city models, *visibility analysis*, *energy demand estimation*, *emergency response, shadow estimation, utility management, noise propagation, indoor navigation, infrastructure planning, 3D cadastre* or *solar potential estimation* can be named (see: Figure 2.3).

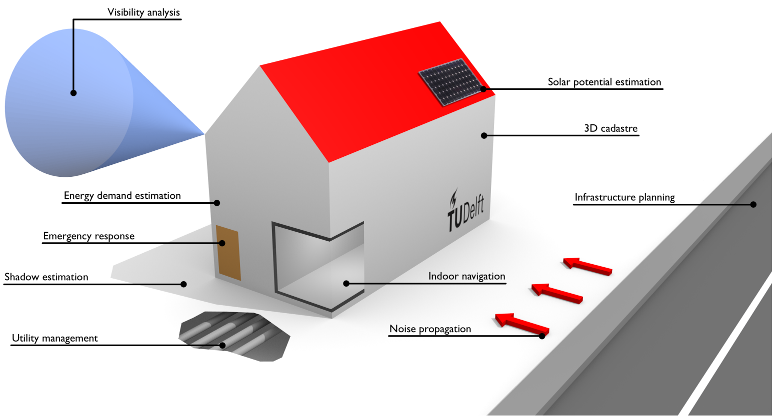


Abbildung 2.3: Use cases (UCs) of 3D city models [12].

These UCs can be assigned to different *application domains* of 3D city models and consist of various *spatial operations*. Application domains are applied UCs in the context of a specific domain, to solve an application problem [12, p.2846]. As examples for application domains, *marketing, energy applications, infrastructure planning, disaster management, insurance, urban studies or predicting air quality* can be named [12].

Use cases normally consists of various *spatial operations*. These operations range from *line of sight between two points*, the *volume of building solids* to *direction of noise* [12]. Figure 2.4 shows the relations and overlaps between spatial operations, use cases and applications.

The *data basis* of 3D city models is generated by different acquisition techniques like photogrammetry and laser scanning, synthetic aperture radar, extrusion from 2D footprints, architectural models and drawings, procedural modelling, handheld devices and volunteered geoinformation Biljecki et al. [12].

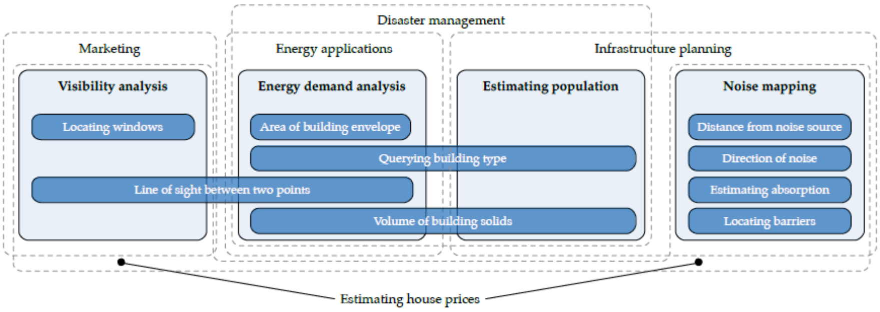


Abbildung 2.4: Relations and overlaps between spatial operations (dark blue), use cases (light blue) and applications (dashed stroke) [12].

2.2.2 LOD

The Level Of Detail (LOD) indicates geometric details of 3D city models and denotes the adherence of the model to its real-world counterpart [11]. The LOD can be seen as one of the most important characteristic of a 3D city model with implications on usability. The classification of the LOD is varying depending on the capabilities of acquisition practices, the underlying data model standard (e. g. CityGML) and the tasks addressed [10]. Orientating at the data format CityGML (see Section 2.2.3), for buildings five different LODs can be mentioned (see Figure 2.5), which are described by Kolbe [64] as follows:

- LOD0: a representation of footprints and optionally roof edge polygons
- LOD1: a coarse prismatic model
- LOD2: a model with a simplified roof shape - with multiple semantic classes (e. g. roof, wall)
- LOD3: an architecturally detailed model with windows and doors
- LOD4: include indoor features in a LOD3 model

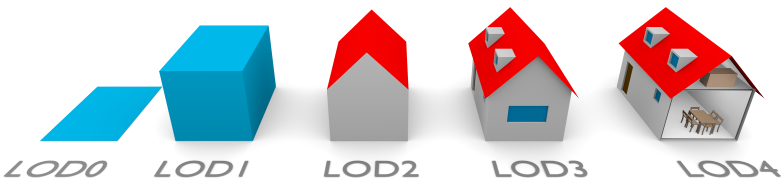


Abbildung 2.5: Five LODs of CityGML 2.0 [10]

The Open Geospatial Consortium (OGC) defines LODs also for further objects (e. g. city furniture, vegetation objects) [103]. The proposed accuracy requirements of cities and containing objects are summarized in Table 2.1.

The accuracy requirements (Table 2.1) have been seen as an discussion proposal for CityGML 2.0 and will be outdated, after the implementation of CityGML 3.0 [103]. In research, new concepts and frameworks to define discrete and continuous LODs were proposed [11]. Biljecki et al. [10] e. g. suggests the further development of the LOD concept of five LODs in a refined set of 16 LODs to solve identified shortcomings [10].

2.2.3 Data format - City Geography Markup Language (CityGML)

CityGML2.0 is an OGC standard of representing and storing 3D city models. It is a eXtensible Markup Language (XML) based data format, which allows the interacti-

	LOD0	LOD1	LOD2	LOD3	LOD4
Model scale description	regional, landscape	city, region	city, city districts, projects	city districts, architectural models (exterior), landmark	architectural models (interior), landmark
Class of accuracy	lowest	low	middle	high	very high
Absolute 3D point accuracy (position/height)	lower than LOD1	5/5 m	2/2 m	0.5/0.5 m	0.2/0.2 m
Generalisation	maximal generalisation	object blocks as generalised features; >6*6/3 m	objects as generalised features; >4*4/2 m	object as real features; >2*2/1 m	constructive elements and openings are represented
Building installations	no	no	yes	representative exterior features	real object form
Roof structure/representation	yes	flat	differentiated roof structures	real object form	real object form
Roof overhanging parts	yes	no	yes, if known	yes	yes
City Furniture	no	important objects	prototypes, generalized objects	real object form	real object form
Solitary Vegetation Object	no	important objects	prototypes, higher 6 m	prototypes, higher 2 m	prototypes, real object form
Plant Cover	no	>50*50 m	>5*5 m	<LOD2	<LOD2

Tabelle 2.1: *proposed accuracy requirements LOD0-4 of CityGML 2.0* based on Open Geospatial Consortium [103]

on with different encodings (e. g. Geography Markup Language (GML) or Structured Query Language (SQL)) [100]. CityGML defines relationship, the description of 3D features and objects and the Level Of Details (LODs) within 3D city models [103]. Represented aspects of a CityGML data model are therefore: 3D geometry, 3D topology, semantics and visual appearance. UCs of CityGML data models can be divided into the groups *archiving, visualisation, navigation, simulation and analysis* [100].

The CityGML2.0 data model architecture is build up module-based and contains class definitions for different types of objects within 3D city models. The CityGML data model architecture can be divided into a *core module* and *thematic extension modules* as well as Application Domain Extensions (ADEs) (see Figure 2.6).

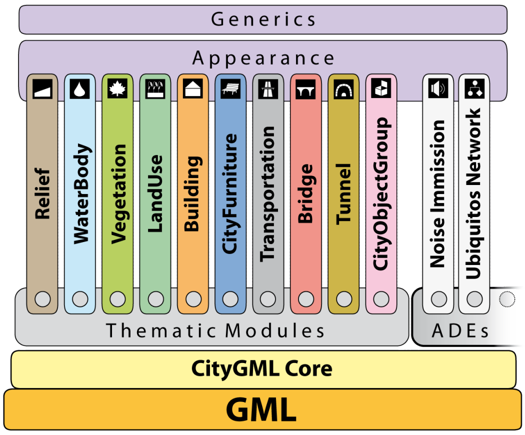


Abbildung 2.6: CityGML 2.0 architecture [137]

The core module covers the basic concepts and components of the CityGML data model and conducts the data frame for the thematic extension modules or the ADEs. CityGML2.0 contains ten different thematic extension modules, which are: *Relief, WaterBody, Vegetation, LandUse, Building, CityFurniture, Transportation, Bridge, Tunnel CityObjectGroup* [103].

If an application domain is not covered by the available thematic extension modules, the use of *Application Domain Extensions (ADEs)* is recommended. ADEs allow to add new features or definitions of new object types, which were not covered by the thematic extension modules. ADEs also have the task to support interoperability between different formats (e. g. CityGML and Industry Foundation Classes (IFC)[2]). The ADE has to be defined in a XML Schema Definition (XSD) [103] or with Unified Modeling Language (UML). The extension is thereby formally specified and preserves the semantic structure of CityGML [9]. Biljecki et al. [9] identifies 44 ADEs for a range of applications (e. g. from energy analyses, harmonisation of national data standards) and a variety of purposes.

In the scope of this master thesis, the conceptual 3D city model is affected by the thematic extension module *Buildings*. This master thesis is referring to CityGML 2.0., the latest OGC approved version up to now. Detailed information about CityGML 3.0 and the developing status can be found under [67, 100].

2.3 DIMENSIONS OF A GIS

This section describes the theoretical background of geometric, topological, thematic and temporal dimensions applied in a GIS. According to Bill [13] in the field of mathematics the term *dimension* describes the number of degrees of freedom of a

2 Industry Foundation Classes (IFC) is a data model which describes construction, architectural and building data. It is an open file, platform neutral and object-based collaboration format of Building Information Modeling (BIM) projects.

motion or location in a given space—a geometry based approach. In GIScience the definition of dimensions is extended by three more domains, namely topology, thematic and dynamic. As a consequence the dimensions of geographical features can be distinguished into *geometrically*, *topologically*, *thematically* and *temporally* dimensions [13, 135]. The following section will describe the characterisation of theses four different dimensions.

In the scope of this master thesis, scale dimension or multidimensional modelling will not be discussed. For more information van Oosterom and Stoter [135] can be recommended.

Geometric dimension

Geometry describes the position and shape of objects in space [13]. In a GIS spatial data can differ regarding its geometric dimension. A plane map, for example, shows a different geometric dimension than a DTM or a building model. With respect to the geometry, a GIS can be divided into following geometric dimensions [13]:

- *Two-dimensional* - $(2D,(x,y))$, geometric data refer to x,y-coordinates and do not contain elevation data (planimetric map).
- *Two-plus-one-dimensional* - $(2D+1D,(x,y)+(z=z(x,y)))$, a planimetric map is supplemented by a DTM given as a 3D-contour lines model or 3D-surface model.
- *Two-and-half-dimensional* - $(2.5D,x,y,z=z(x,y))$, the geometric date refer to x,y-coordinates and contain elevation data as attribute value.
- *Three-dimensional* - $(3D,(x,y,z))$, the x,y,z-coordinates in sufficient density are available for the whole area. A distinction is made between 3D-contour line models , 3D-surface models and a volumetric model.

Topological dimension

Topology describes relative spatial relationships of objects to each other [13]. According to Bill [13] the dimension of the topology is defined in terms of its planar extent. The topological dimension can be categorised with the so called *cell-tuple model* as following:

- *0-cell* represent points (topologically termed as `nodes`)
- *1-cell* represent lines (topologically termed as `edges`) which form the foundation of the contour line model.
- *2-cell* closed line polygons which represent the surface (topologically termed as `face`[3])
- *3-cell* represent uncomplex bodies (topologically termed as `solids`) which are assembled in a further step to complex bodies.

In a Cell-tuple model, contour line models consist of nodes and edges, surface models consist of faces and the volumetric model consist of solids. For complex city models the cell-tuple model can reach unmanageable amounts of data [147]. Chen et al. [21] therefore propose the utilization of the *Simplified Spatial Model (SSM)*, which is an optimized spatial model in terms of data storage size (see Figure 2.7) [21, 147].

The SSM model consists of four geometric objects (`point`, `line`, `surface` and `body`) and two constructive objects (`nodes` and `faces`) [21]. The objects are according to Zlatanova [147] described as follows: `point`—a spatial object, which has no shape or size but position; `line`—a spatial object, which has length and position; `surface`—an

3 two-dimensional topological primitive [59]

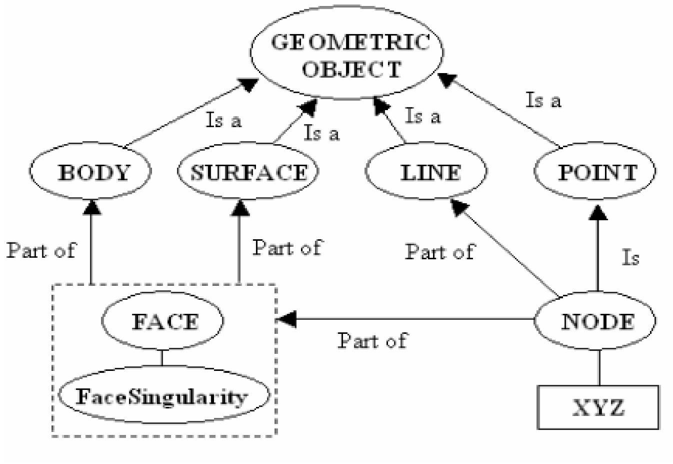


Abbildung 2.7: SSM for topological operations [21].

abstract spatial object with area and position; `body`—a spatial object which feature volume and position; `nodes`—represent points and lines; `faces`—represent surface and bodies [21]. For more detailed information relating to topological dimensions and operations Bill [13], Chen et al. [21], Zlatanova [147] can be recommended.

Thematic dimension

In a GIS, spatial elements and phenomena are represented as thematic layers or themes (e. g. Figure 2.8). Each layer consists of one type of feature data (vector data—points, lines or polygons) or an image (raster data model) [41]. Bill [13] describes a GIS as *thematically one-dimensional*, if only *one* theme (one feature or layer) is discussed. As example for a thematically one-dimensional GIS, a 3D-contour line model can be listed. This approach allows the conclusion, that n themes lead to a *thematically n-dimensional* GIS [13]. Figure 2.8 i. e. shows a thematically five-dimensional GIS.

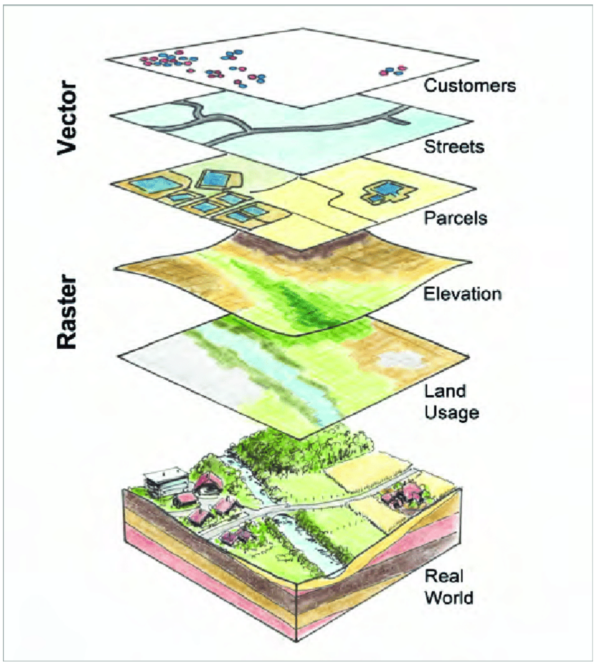


Abbildung 2.8: Thematic layers or themes of a GIS [41] - a five-dimensional thematic model (Illustration: Karl Herweg).

Temporal dimension

Time as an independent dimension is regarded as one-dimensional. In the context of GIS, time is coupled with the spatial reference and can be seen as a dimensional extension of space. Time and space form a *four-dimensional space-time* $(4D, (x, y, z, t))$. Time takes the role of a dimension [13]. In combination with the geometric dimensions, according to Bill [13], the following constellations therefore emerge in the GIS context:

- $2D + time(x, y, t)$ - time is added to two-dimensional geometry data (e. g. in the field of historical GIS)
- $2.5D + time(x, y, z = f(x, y), t)$ - time is added to two-and-half-dimensional geometry data (e. g. in the field of landfill management)
- $3D + time = 4D(x, y, z, t)$ - time is added to three-dimensional geometry data (e. g. in the field of urban planing, meteorology, etc.)

2.4 GEOVISUALISATION

This section describes the theoretical background of 3D geovisualisation processes, data- and presentation space and advantages or disadvantages of applied 2D and 3D VAs.

Geovisualisation processes were scientifically treated by Cartography, Computer Science and the field of Human-Computer Interaction (HCI) [80]. Gartner [42] therefore describes Cartography as a science of communication processes. Aim of the communication process is to transmit spatial data to a user by using, transmitting and finally decoding codes [42].

According to Ward [139], the first step of the design of a new visualisation is the analysis of the type of *data* available and the type of information the viewer hopes to extract. As regards the latter, visualisation can have an explorative character, a hypothesis confirming character or an results of analysis representing character. I. e. visualisation in data exploration is used to convey information, identify structures, patterns, anomalies, clusters, trends, relationships and to discover new knowledge. The term *visualisation* is therefore defined as ...

> '[...] the communication of information using graphical representations.'[139]

Or, as ...

> '[...] a form of visual communication, [which] can be described as the process of transforming (non-visual) data into artefacts accessible to the human mind.'[27]

Based on these definitions the major purpose of *geovisualisation* lays in the effective communication of *spatial data*. But, the effectiveness of communication, decision making and human problem solving performance varies with different forms of presentation. Advances in rendering hardware and increasing computing power over the last decade allow the interactive visualisation of large-scale and complex datasets [27]. The tasks or aims of big data visualisation achieved by adjusting filters, changing colour palettes, and novel visualisations are to search for (1) relationships, (2) clusters, (3) gaps and (4) outliners within the dataset [117].

2.4.1 Visualisation processes

The visualisation process in the scientific field of Cartography is described by Kolacny [62]. According to his research, spatial information has to pass different filters

(e. g. scale, projection, graphics or generalization), has to be coded in a map and afterwards has to be decoded by various user-dependent filters (e. g. viewing time, prior knowledge, cartographic expertise, etc.) (see Figure 2.9) [42].

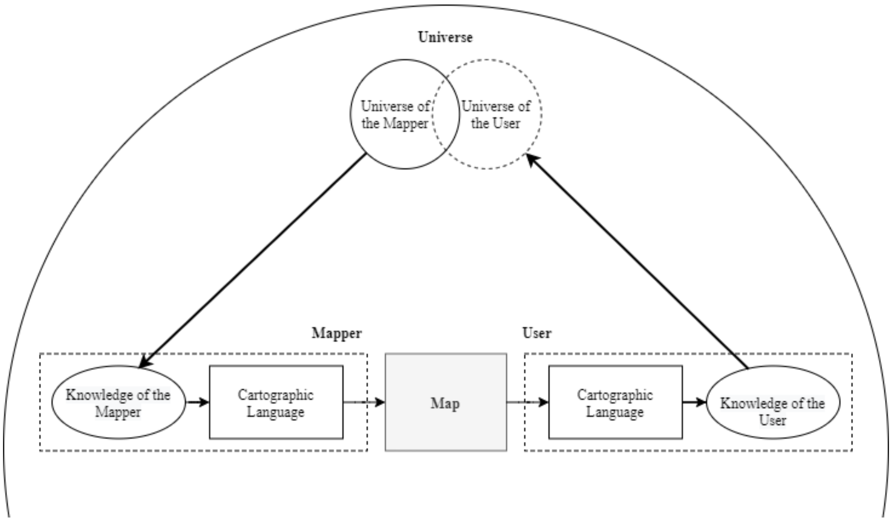


Abbildung 2.9: *Communication processes in Cartography* — based on Kolacny [62].

The scientific field of HCI divines the visualisation process into a computer and a human based processing field. Within the computer, the raw data is transformed and rendered. On human side, the visualised information is recognized and combined to knowledge (see Figure 2.10).

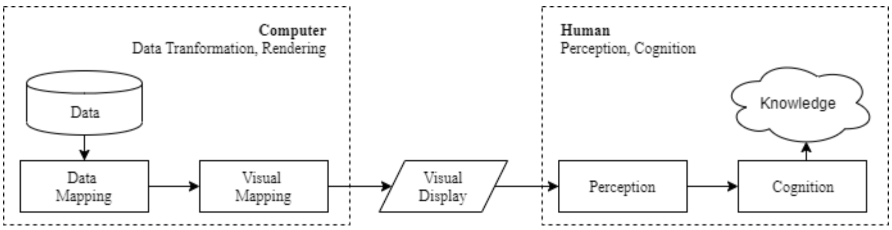


Abbildung 2.10: *Visualisation model* — based on Ward [139].

The *data* to be visualized has to be structured in a format that ensures easy modification and rapid access [139].

The main aspect of the computer-sided visualisation pipeline is the mapping of data values to graphical primitives or their attributes. This process is named *rendering*. Within the 'data to visual mapping' process, often preprocessing steps such as scaling, shifting, filtering, interpolating or subsampling are conducted [139].

The connecting link between computer and human in the visualisation model is the *visual display*, which represents the rendered data in a Graphical User Interface (GUI). Graphical User Interface (GUI) is one form of a user interface, which allows to interact and communicate with information through graphical icons. According to Held et al. [52], it can be seen as the 'main gate' to the application. GUI is based on the WIMP paradigm, which consist of four elements: *windows*, *icons*, *menus* and *pointer* [52].

According to literture, following features are necessary to visualise the real world within a GUI sufficiently: (1) appropriate modelling of physical objects, (2) lighting and shadowing, (3) definition of viewpoints and (4) photo-realistic texturing. Real-time interactive navigation attributes (e. g. walk-through, flying, rotating, etc.) allow to interact with the virtual world and to exam objects. Maintenance of LODs and multi-resolution texturing decrease the performance requirements [52].

Perception is described in literature as a process of *recognizing*, *organizing* and *interpreting* sensory information. The perception in visualisation is influenced by the visual features *colour*, *texture*, *motion* and *memory issues*. The binding of the recognized and organized sensory information to knowledge is influenced from cognition abilities.

As further literature, Bertin [8], Gartner [42], Interaction Design Foundation [57], Kolacny [62], MacEachren and Kraak [80], Mazza [83], Shneiderman [117] and Williams et al. [142] can be recommended.

2.4.2 Data- and presentation space

The process of visualisation is also influenced from *data space* and *presentation space* [27].

Spatial data always consists of defined observation points which require *spatial reference* and given observed data values. This allows the differentiation between *independent* variables v (e. g. spatial coordinates) and *dependent* variables d (e. g. temperature, speed) [27, 61]. The independent variables define a n-dimensional *reference space (R)*, which is, according to Dübel et al. [27], typically 2D or 3D ($n \in \{2,3\}$). The dependent variables define an m-dimensional *attribute space (A)*, which can be multidimensional ($m \in \mathbb{N}$) [27].

Presentation space is constructed from *graphical elements*. These elements consist of visual variables like *size*, *shape*, *colour* and *texture* Bertin [8]. The concept of visual variables allow a systematization in categories such as *appearance*, *representation data type of the visualisation artefacts*, *handling of time* or *dimension* (see Table 2.2) [27, 110]. Focusing on the dimensional aspect, 2D presentation consists of 2D graphical elements (e. g. points, lines and polygons). On the other hand, 3D presentations can consist of 2D and 3D graphical elements (e. g. solids, free-form-surfaces) [27].

Category	Criteria of classification
Appearance	*Photorealistic* or *non-photorealistic* rendering
Data type of the visualisation artefacts	*Raster* or *vector* graphics
Handling of time	Static or dynamic approach
Dimension of presentation	2D or 3D

Tabelle 2.2: Systematization of aspects contributing to the *presentation space* Dübel et al. [27].

Spatial data consist of independent and dependent variables which define the n-dimensional *reference space* and the m-dimensional *attribute space*. As described earlier, graphical elements can also be distinguished according to their dimension.

This circumstances require a classification of VAs regarding the combinations of 2D and 3D presentations of the attribute space (A) and reference space (R). For classification Dübel et al. [27] introduces the notation: $(A^i \otimes R^j)$, with $i, j \in \{2, 3\}$: the selected attributes are visualized with i-dimensional graphical elements, while the reference space is visualized with j-dimensional graphical elements [27] (see: Figure 2.11).

Due to this characterisation, existing VAs can be categorised as $(A^2 \otimes R^2)$, $(A^2 \otimes R^3)$, $(A^3 \otimes R^2)$ or $(A^3 \otimes R^3)$ [27] (see Figure 2.12).

2.4.3 2D or 3D

Presentation techniques also differ regarding the geometrical dimensions (see Section 2.3). The choice whether to use 2D or 3D for data visualisation depends on *data complexity*, *display technology*, *the task* or *application context* [27].

2D or 3D VAs leads to different advantages and disadvantage related to perceptual and technical aspects, such as *occlusion*, *clutter*, *distortion* or *scalability* [27]. Rese-

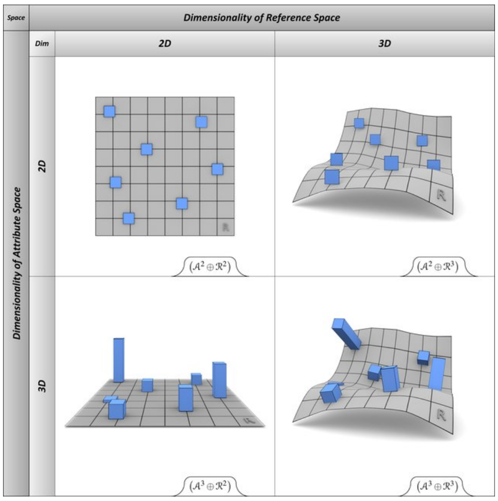
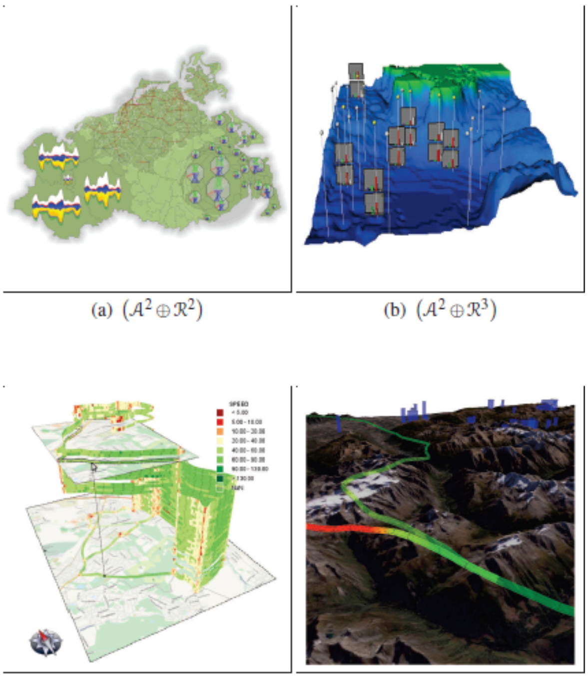


Abbildung 2.11: Systematization of visualisation techniques based on dimensionality (2D or 3D) of the attribute space (A) and reference space (R). The vertical axis shows the dimensionality—2D or 3D)—of the attribute space (A). The horizontal axis shows the dimensionality—2D or 3D)—of the reference space (R). [27].



(a) $(\mathcal{A}^2 \oplus \mathcal{R}^2)$ (b) $(\mathcal{A}^2 \oplus \mathcal{R}^3)$

(c) $(\mathcal{A}^3 \oplus \mathcal{R}^2)$ (d) $(\mathcal{A}^3 \oplus \mathcal{R}^3)$

Abbildung 2.12: Examples of visualisation techniques for $A^i \otimes R^j$, with $i, j \in \{2, 3\}$ - (a) 2D diagrams on a 2D map; (b) 2D diagrams on billboards on 3D surface; (c) 3D trajectories on a 2D map; (d) 3D trajectory in 3D terrain [27].

arch further indicates that 3D presentations show higher context perception than 2D presentation in case of a higher number (>250) of objects to be presented [136]. According to Tory et al. [128], 3D can be effective for approximate navigation and relative positioning. 2D is more suitable for precise measurement and interpretation [27]. Combinations of 2D and 3D increases confidence during problem solving [128]. On the other hand, case studies show that there are no significant effects of 2D and 3D presentation on spatial memory [24]. When participants are asked, regarding city models, in most cases they prefer 3D over 2D [12]. This preference is often due to wrong assumptions and the faith in realistic displays. This common-sense misleading intuitions about how to best visualize spatial data is termed *naïve cartography*

[51]. In addition to the classical structuring of presentation techniques into 2D or 3D, a further subdivision by distinguishing presentations of *attribute space* and *reference space* — according to their dimensionality — can be made [27].

2.5 EVALUATION OF VISUALISATION APPROACHES

To compare and evaluate the implemented visualisation approaches VAs and to subsequently answer the research question it is important to identify a suitable evaluation method. The goal of evaluation methods is to improve interface design in a specific system. Or, as Lazar et al. [68] mentioned to answer the question: 'How to make a specific interface better?' According to Ward [139] aspects of visualisation like computational or memory performance, data limitations and the degree of occlusion, complexity, usability and accuracy can be evaluated. In the scope of this master thesis the focus lies on the usability of the VA. The following chapter therefore lists several methods for evaluating visualisations and justifies the selection of the finally implemented evaluation method.

2.5.1 Methods for evaluating visualisations

Methods to evaluate and compare different VAs can be classified differently. One approach in literature is to divide these methods based on their character in *automatic* or *empirical* and in *formal* or *informal*. Automatic evaluation means that the usability measures are computed by running a User Interface (UI) specification through a program. Empirical evaluation means that the usability is assessed by testing the UI with real users. Formal evaluation applies exact models and formulas to calculate usability measures. Informal evaluation is based on rules of thumb and focus on the skill and experience of the evaluator [96].

According to Nielsen [95] empirical informal testing methods can be favoured due to the estimation that automatic or formal methods do not work, do not scale up well or are difficult to apply. In literature empirical methods are therefore the main approach to evaluate user interfaces. The informal character makes these inspection methods highly cost-effective.

Another approach to group evaluation methods is to separate them, based on who is evaluating. Lazar et al. [68] differentiate processes or activities that aims to improve the ease of use of an interface into *expert-based testing*, *automated testing* and *user-based testing*.

Regarding evaluating visualisation approaches Ward [139], Lazar et al. [68] and Nielsen [93] were identified as key literature and can be recommended to gain more detailed information.

Due to the recommendations in literature, the scope of this master thesis, and based on the advantages of expert- and user-based testing, the following section provides a brief overview on the most common techniques for expert-based and user-based testing, while the description of automated testing will be waived.

Usability tests

According to Stone et al. [126] usability tests concentrate on the evaluation of the five E's, namely *effectiveness, engagement, efficiency, error tolerancy* and *easiness to learn*. This user-based testing technique is often carried out in a controlled environment over a short period of time [139, 68]. Whilst users are performing tasks, types of difficulties, commonly used features and their level of satisfaction/comfort with the tool are noted. The results of the evaluation indicates if previously defined usability goals or requirements have been met or not [139]. Usability tests often contain hypothesis testing, tight controls, control groups and a large number of participants [68]. A main disadvantage of usability tests is the complexity and the large number of participants needed. As practical example and for further scientific specification Billger et al. [14] can be recommended.

Field tests

Field tests are performed in the natural environment of the typical user and can last for weeks or months [105]. This method attempts to assess usability after a new technique or tool becomes an integrated part of users activity. The results of this form of evaluation are in most cases qualitative. Clarification and improvement in functionality of the visualisation technique or tool can rise when users are encouraged to submit questions and critiques [139].

Although field tests are suitable to identify UPs, they have the disadvantage of being carried out over a long period of time and that a high number of participants is necessary.

Use cases and case studies

Use cases and case studies represent artificial or real examples of an implementation of the developed technique or tool to users. With use cases and case studies it can be shown, how the developed technique or toll can be used in performing a given task or in solving a particular problem. A major challenge when choosing uses cases and case studies for evaluation purposes is, that they have to be sufficiently realistic to convince the users or evaluators with a particular task to perform that the tool is similar to the own task and that it will effectively support it [139].

Expert reviews

In literature expert reviews are also known as expert inspection or usability inspections [68]. The experts have to test the applicability and try to identify UPs in an early stage of the development of a new visualisation technique or tool [139, 129].

Conclusion

Usability test were not considered as appropriate method within this master thesis, due to the complexity and the large number of participants required to implement the method. Field test also have been rejected, due to the circumstance that the tests have to be carried out over a long period of time under use of a high number of participants. The implemented VAs are at an early stage of the development. Therefore the implementation of a case study is not an adequate method to identify the UPs.

Due to the circumstance that only a small number of participants is necessary and further recommendations in literature [93, 97, 95, 129, 148, 112] expert-based testing was chosen to evaluate the implemented VAs. Therefore the following Section 2.5.2 describes the characteristics of expert reviews in more detail.

2.5.2 Expert-based testing

Expert-based testing aims at finding *usability problems* or as Lazar et al. [68] states by finding *flaws-areas* of the interface that need improvement [95]. The expert inspection can be performed early in the usability engineering life-cycle. Expert-based tests can be carried out with a small number ($n = 5$) of qualified reviewers [129]. These reviewers either have to be experts in visualisation or domain experts.

Lazar et al. [68] lists heuristic evaluation, cognitive walkthroughs and consistency inspection as the most common types of expert review methods.

Consistency inspection

During a consistency inspection, experts review web pages or a series of screens for issues of consistency in e. g. layout, colour, typeface, terminology or language. This is often done with the addition of sets of style guidelines [68]. Up to now, however, no style guidelines for the practical implementation are available, which makes an easy application difficult.

Cognitive walkthrough

In a cognitive walkthrough, interface experts simulate users and 'walk through' a series of tasks. Hereby, the experts must have experience with general interface design, know who the users are and what task the users are expected to perform [68] . The exploratory nature of this method gives an understanding of how users might interact with an interface. However, this method has still limitations. According to literature [68] the most serious disadvantage ot this method is its task-based character. It is therefore not as productive as user-based testing.

Heuristic evaluation

Heuristic evaluation is an expert-based inspection method proposed by Nielsen [93]. The aim of the evaluation method is to identify usability problems by using heuristics. Heuristics are usability principles which allow to focus the evaluation on certain predefined areas (e. g. spatial perception) [142]. Therefore Tory and Moller [129] recommend three to five experts with experience in data display or in usability. Heuristic evaluation can be applied within the fields of HCI, information visualisation or geovisualisation [83, 134].

To gain deeper insights in HE following literature can be recommended: Lazar et al. [68], Nielsen [95], Quiñones and Rusu [111], Unrau and Kray [134] and Ward [139].

2.5.3 Concluding Remarks

Due to the early stage of the implemented VAs and time limit user-based testing methods were not considered as method to identify UPs and their severity. Therefore the focus of the master thesis lies on an expert-based evaluation method.

A consistency inspection is not applied in the scope of my master thesis, as there are no style guidelines dealing with 3D air temperature visualisations within a 3D city model at this time.

Cognitive walkthroughs have a task-based character and are therefore not as productive as user-based testing. Due to this characteristic cognitve walkthroughs are not considered as the appropriate evaluation method within this master thesis.

As Quiñones and Rusu [111] points out the *advantages* of performing a heuristic evaluation are: (I) it is less expensive compared to other methods in terms of number of usability experts, time and resources; (II) it does not require extensive planning; (III) it is appropriable in the early stage of the development; (IV) many problems can be found and (V) no users are needed.

The *disadvantages* of performing a heuristic evaluation are: (I) there is no systematic way to generate solutions to the problems encountered; (II) results of an expert review depends on experts qualification and (III) can identify different problems than test with end users [111].

Due to fact that HE are less expensive in resources, appropriable in the early stage of the development (formative evaluation), suited to detect a large number of existing UPs and also enable experts to indicate further improvements, the HE was chosen as appropriate method to evaluate the applied VAs. Chapter 6 describes used elements of this evaluation method in detail.

3 RELATED WORK

This chapter outlines related work dealing with potential *visualisation approaches* VAs and *visualisation applications*, which allow to visualise air data within 3D city models. From the key findings, a conclusion is drawn which VA is suited to be practically implemented in the scope of this master thesis. Based on related work guidelines how to implement air temperature data in a 3D city model are drained.

3.1 VISUALISATION APPROACHES

In the scope of this master thesis the term visualisation approach (VA) can be equated with 'visualisation technique' or 'visualisation method'. The VAs have to be suited to visualise the air temperature data of a *3D Cartesian grid*. Cartesian grids consist of unit squares (see Figure 3.6b) or unit cubes (see Figure 3.1). Within the scope of this master thesis, the term 'voxel layer', used by Environmental Systems Research Institute, Inc. (Esri) [36], is equated with the term '3D Cartesian grid'. The visualisation of the 3D Cartesian grid can be done by using different graphical primitives like billboards, cubes or spheres (see: Section 3.1.1 and Section 3.1.5).

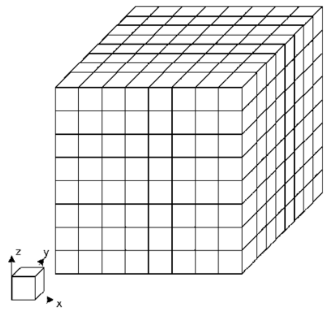


Abbildung 3.1: *3D Cartesian grid* [43]

For the selection of potential VAs, two key criteria have been defined. The first criterion is that (1) the VA allows to visualise on city scale. The second criterion is that (2) no information is lost—e. g. caused by a decrease of spatial resolution—during the visualisation process. Based on findings of the literature research and narrowed down following the two key criteria, the VAs 'Point Cloud', 'Cross Section', 'Isosurface', 'Polygon mesh' and '3D polygon' have been identified to be suited for the scope of this thesis. Consequently, related work dealing with these VAs has been searched for and is presented in the following sections.

3.1.1 Point Clouds

The VA *point cloud* consist of points, which contain geometric coordinates and attribute value. In general point clouds are often based on information generated by 3D-laser scanners and LIght Detection And Ranging (LiDAR) techniques and consist of huge amounts of data [13]. The visualisation of each point information is done by colouring the 2D billboards, which rotate to face the camera. Billboards can be defined as textured polygon based on the billboard alignment techniques 'view plane' and 'viewpoint' [3] (see: Figure 3.2). In the scope of this master thesis the viewpoint oriented alignment technique was applied (see: Section 5.2).

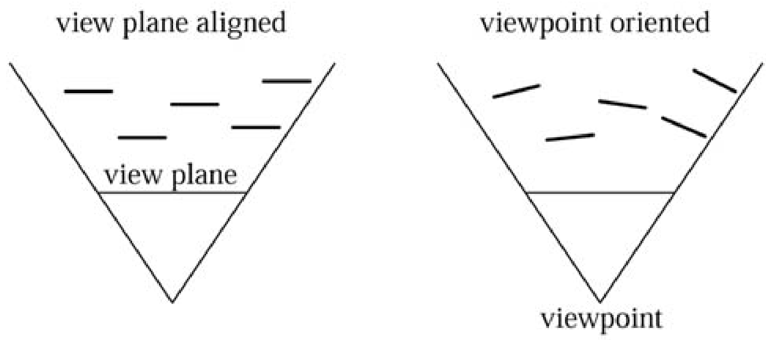


Abbildung 3.2: Billboard alignment techniques *view plan* and *viewpoint* oriented billboard [3]

Illustrative showcases for the visualisation of air data, using the VA point cloud, can be extracted from the example gallery of `CesiumSandcastle` [20] (see Figure 3.3c and Figure 3.3d). The live code editor and example gallery shows different styles of point clouds and its underlying JavaScript (JS) code. The style options for each points reach from simple colouring, colour ramping, adding of transparency to change of the point size, depending on attribute values of the data base. The browser based tool allows to visualise continuous air data dynamically within a 3D data and 3D representation space.

As further example of this methodological approach, Chow [22] can be mentioned. Chow [22] visualises dynamic atmospheric pressure by using *billboards*, structured as a 3D Cartesian grid (see Figure 3.1). The raw data was provided by an meteorological service on a regional scale. Within this visualisation, users were able to filter variables and control the time axis. The browser based demo was applied within the Cesium visualisation pipeline [22].

The showcases presented in the example gallery of CesiumSandcastle as well as the showcase implemented by Chow [22] were implemented in a virtual globe, containing surface texture and a underlying DTM [20, 22]. The showcases do not show the combination of point clouds and 3D city models.

A similar visualisation approach is shown in a conceptual study conducted by Stahre Wästberg et al. [125] (see: Figure 3.3a). Aim of the study was to develop a visual concept for 3D city models which visualise air pollution dispersion from a street perspective at different elevation levels. Several different visualisation approaches like vertical and horizontal layers were developed within a 3D city model of the study area, the city of Gothenburg. The visualisation of vertical points (see: Figure 3.3a) can be seen as the most promising approach to visualise temperature data with a 3D city model on city scale. This visualisation approach is based on continuous and static air data, calculated by `SoundPlan`. The results were extracted in grids for 16 vertical layers, by using the geostatistics interpolation method *'kriginging'* [125]. In this showcase, due to the statical approach and the used visualisation application a navigation through the data space or an interaction with elements of the represented urban area is however not possible. According to literature statical 3D geovisualisation leads to occurrence of distortion and occlusion. These occurring problems can be minimized by using a manipulable model which allows to change the perspective and move through the data space. This leads to the conclusion that a visualisation application has to be selected, which allows to create manipulable models.

Although the methodological approaches of Chow [22] and Stahre Wästberg et al. [125] show some limitations (e. g. not on city scale or implementation of a statical approach) the used VA point clouds appears promising, due to its ability to represent a huge amount of air temperature data and the implementability in the 3D web

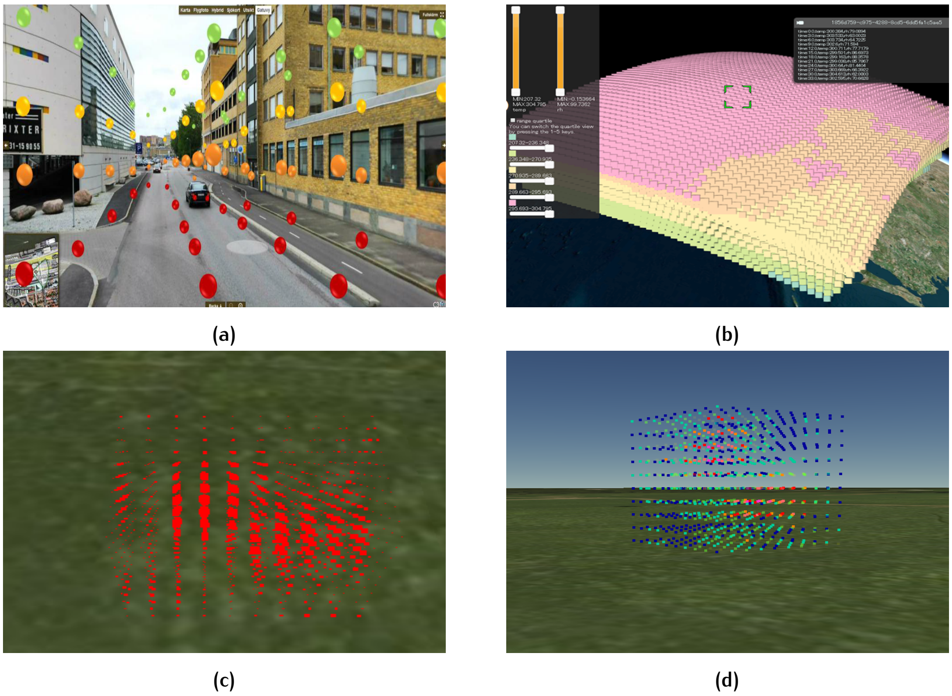


Abbildung 3.3: (a) vertical points visualisation [125], (b) point cloud on continental scale [22] (c) point cloud based on varying point size (d) point cloud based on varying point colour [20].

application Cesium. The implementation of VA point cloud in Cesium further promises to allow the visualisation of 3D air temperature data within a 3D city model, which leads to the conclusion to apply VA point cloud in the scope of this master thesis (see: Section 5.2).

3.1.2 Cross Section

The VA *cross section* can be mentioned as another VA, which allows to visualise 3D temperature data. This VA can be visualised in ArcGIS Pro. One or more cross sections allow to render the temperature value of a 3D data space at a 2D plane [35]. In comparison to the VA 'point cloud', in the VA 'cross section', the section or 2D plane can be described as a single billboard which is not automatically oriented to the camera and features multiple attribute values (see: Figure 3.4).

Up to now, no related work is yet based on this VA. There are only guiding tutorial available to create showcases. The described showcases deal with the visualisation of geological survey, marine data or riverine water columns [36]. However, up to now, no showcase could be identified, actually implementing cross sections within a 3D city model, while it seems obvious, that such implementation should be feasible. Therefore, and due to the fact, that the VA 'cross section' allows to represent 3D data and the availability of guiding tutorials [35], this VA was implemented (see: Section 5.3).

3.1.3 Isosurface

The identified VA *isosurface* allows to visualise 3D temperature data at a certain value (e. g. 25°C). This VA can be visualised in ArcGIS Pro. An isosurface can be defined as a surface representing a specific value [33].

Again, up to now, no related work dealing with the implementation of the VA 'isosurface' in a 3D city model could be identified. But, comparable with VA 'cross section', guiding tutorials were available, which show how to create showcases. Identi-

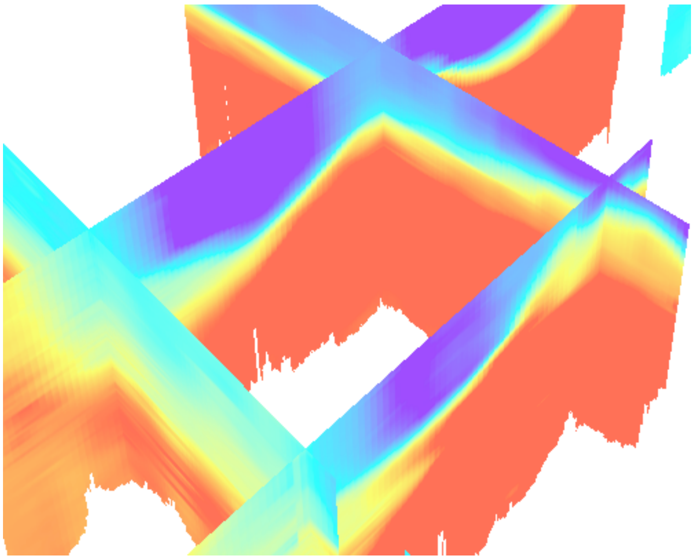
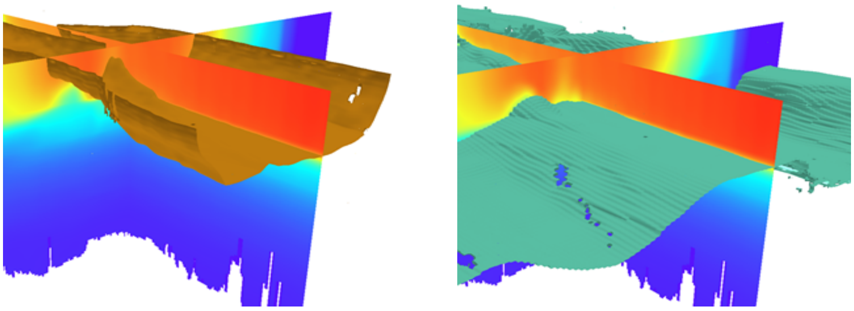


Abbildung 3.4: *Cross Sections* representing marine data [35].

fied showcases deal with the visualisation of threshold values regarding geological survey, marine data or for pollutants in the atmosphere (see Figure 3.5).



(a) (b)

Abbildung 3.5: Isosurface representing (a) marine temperature value at 25°C (in brown) and (b) saturation of oxygen at a value of 70 (in turquoise) [33].

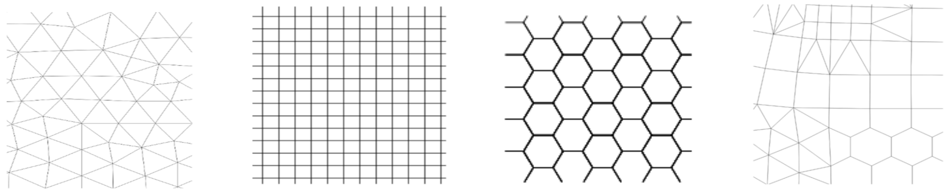
Due to the fact, that the VA 'isosurface' allows to visualise single values of 3D air data and the availability of guiding tutorials [33] this VA was assumed to be promising solution and therefore selected for the implementation (see: Section 5.4).

3.1.4 Polygon mesh

Based on the findings of the literature research, *polygon meshes* were identified as further VA to visualise air data in a 3D city model. Polygon meshes consists of vertices (nodes), edges and a set of faces in 2D or 3D. Vertices contain the x,y,(z)-value in the coordinate reference system of the layer. Edges are connecting pairs of vertices. Faces are a set of edges forming closed shapes. Depending on their structure, meshes can be classified as e. g.triangular, quadrilateral, hexagonal or mixed element mesh (see Figure 3.6) [23, 109].

Edges or faces of meshes can be rendered. If only the edges of meshes are rendered the model is called a *wireframe model*. Wireframe models can be seen as the most basic method, compared to surface and solid modelling, for rending 3D scenes [23]. This technique allows users to visualise the underlying structure and internal components of a 3d model (see: Figure 3.7).

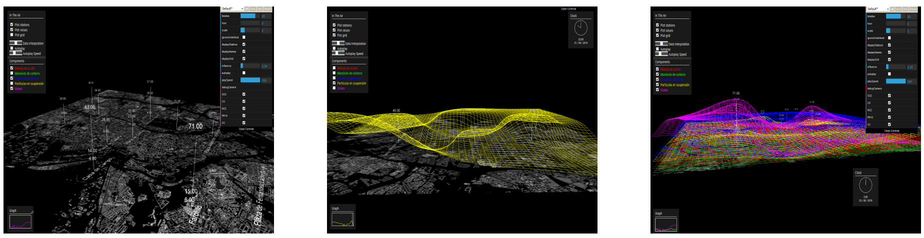
As example for air data visualised by using a polygon mesh, the *In the Air* project can be quoted (see: http://intheair.es/realtime/intheairjs/)[18]. According to



(a) (b) (c) (d)

Abbildung 3.6: Different mesh types (a) *Triangular* mesh (b) *Quadrilateral* mesh (regular grid) (c) *hexagonal* grid [23] or (d) *Mixed element type* mesh [109].

Calvillo [18] the project visualises air pollution data of the study area Madrid. The information is visualized by a wire frame model, consisting of quadrilaterals[1]. The freely available data set show temporal information, which allow a dynamical visualisation. The data set has a discrete characteristic, due to circumstance that the information of the air pollution is generated by several measurement stations distributed in the study area (see: Figure 3.7a). The data value of the air pollution measurement stations are responsible for the offset of the mesh and its 3D character (see Figure 3.7b and Figure 3.7c). The five different layers dealing with carbon monoxide, ozone, nitrogen dioxide, sulphur dioxide and suspended particles were represented by a web-based visualisation tool, based on `Three.js`[2] using Web Graphics Library (WebGL) [17].



(a) (b) (c)

Abbildung 3.7: 'In the Air' project (a) measurement stations of air pollution (b) *single* mesh (c) *multiple* meshs [109].

Although polygon meshes allow to visualise air data, a visualisation of multi-dimensional air temperature data, in particular the visualisation of continuous 3D air temperature data, leads to a reduction of information recognition. Due to this assumption this VA has been dropped. As field of application discrete 3D air data located on a single layer can be proposed (e. g. 'Lärminfokarte' of Austria).

3.1.5 3D polygons and spheres

Another VA identified in the scope of the literature research are *3D polygons* and *spheres*. 3D polygons can be defined as a GIS object which consists of exterior perimeter line and an interior area [31]. The geometrical object sphere is mathematically defined as the surface of a ball [141]. Poulain [107] visualises a 3D Cartesian grids of dynamic cloud cover by using 3D polygons (see: Figure 3.9). To avoid a total loss of information recognition, the 3D polygons were visualised based on the *vanishing cube method*[3] (see: Figure 3.8).

Another showcase invented by Poulain [108] visualises a 3D Cartesian grid of air temperature data. This second showcase is also based on the vanishing cube

1 quadrilaterals: a polygon with four edges and four vertices [49] (see Figure 3.6b)
2 three.js: cross-browser JS library for creating and displaying 3D computer graphics in web browsers [91]
3 vanishing cube method: each data location show a colour which is based on dependent variables and a colour table; a varying transparency factor allows to 'see in' [98].

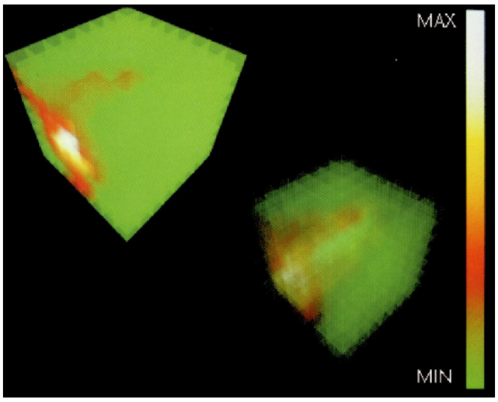
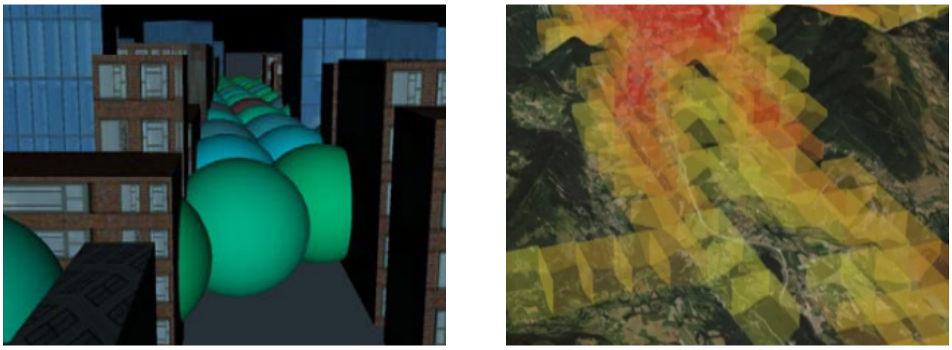


Abbildung 3.8: *Vanishing cube method* of 3D data visualisation [98].

method. Both browser based visualisation approaches were realised with `CesiumJS` [107, 108].

In a further research project José et al. [60] chose coloured *spheres* to represent air data structured as a 3D Cartesian grid (see Figure 3.9). Aim of the concept was to visualise air temperature of the study region of Madrid. Transparency was used to avoid a loss of information. The colour setting was done with RGB codes. Raw data was created by a computational model for multi scale flows. The use case was implemented with a JS based 3D extension of Generalitat Valencia Sistema de Información Geográfica (GvSIG), a Spanish general public licensed GIS [60].



(a) (b)

Abbildung 3.9: 3D graphical primitives (a) sphere [60] and (b) 3D polygon [108].

Although the 3D polygons or spheres allow to visualise 3D air data, an implementation of this VA in a 3D city model was discarded. The decision was based on the assumption that this VA leads to occlusion and in further consequence to a loss of information.

3.2 VISUALISATION APPLICATIONS

Findings of the literature research show that studies, trying to visualise air data, apply to stand alone GIS software (e. g. ArcGIS, GvSIG) for *preprocessing* tasks [60, 125]. But for *visualising* the prototypes in most of the cases 3D web mapping APIs were applied [17, 22, 60, 90, 107, 108]. 3D web mapping is a term which describes online mapping of 3D geospatial data within a Web 3D GIS [13, 52]. 3D web mapping is used in areas such as navigation support, building and facility management, disaster and emergency management and urban planning [29, 52]. *Application Programming Interface (API)* defines interactions between multiple software intermediaries. Examples for 3D a web mapping APIs are: `Cesium`, `ArcGIS API for JavaScript`, `OpenStreetMap API`, `WebGL Earth JavaScript API` or several `Google Maps APIs` [13, 82].

Table 3.1 list the applied visualisation applications of related work. José et al. [60] i. e. implemented a showcase with a JS based 3D extension of GvSIG, a Spanish general public licensed GIS. Chow [22] i. e. visualised dynamic atmospheric pressure based on the JS library `CesiumJS`. Poulain [107] and Poulain [108] i. e. visualised dynamic cloud cover and air temperature data based on the JS library `CesiumJS`.

no.	authors	subject	visualisation app.	framework or library
1	Calvillo [18]	air pollution	IntheAir	`Three.JS`
2	Chow [22]	atmospheric pressure	`Cesium`	`CesiumJS`
3	José et al. [60]	air temperature	`GvSIG-3D`	`osgVP`
4	Morrish and Other [90]	-	`ArcGIS API for JS`	-
5	Poulain [107]	cloud cover	`Cesium`	`CesiumJS`
6	Poulain [108]	air temperature	`Cesium`	`CesiumJS`

Tabelle 3.1: Set of reviewed visualisation application of air data [own table].

All these identified examples are realised by using 3D web mapping tools. According to Held et al. [52] the reason why 3D web mapping tools for visualising prototypes are preferred is that stand-alone applications are often ...

> [...] difficult to use and not very suitable for inexperienced users [52, p.10].

This statement is in line with Mete et al. [84], who describes 3D web mapping as a commonly used approach in GIS applications. In the broad field of 3D web mapping application `Cesium` and `ArcGIS API for JavaScript` are, according to Stähli [124], ...

> [...] the most established 3D web mapping APIs currently available [124, p.3.].

Based on the mentioned assumption that the use of 3D web mapping tools eases the integration of a VA into 3D city models, the implementation of the selected VAs will be realised—if possible—within a 3D web mapping application.

3.3 CONCLUDING REMARKS

This chapter summarises key findings of the literature research regarding related work. These findings contribute to the implementation of three visualisation approaches (VA_1, VA_2 and VA_3) and give guidance as regards the used visualisation applications (see: Chapter 5).

Key finding of the literature research regarding related work are:

- In the examples of related work, meshes, billboards, surfaces and 3d graphical primitives (sphere and 3D polygons) were used as VAs to visualise continuous 3D air data.
- It can be assumed that the visualisation of a 3D Cartesian grid with the VA 'mesh' or with the VA '3D polygon' would lead to occlusions and as a consequence to a reduction of information recognition.
- The VA 'Point Cloud', 'Isosurface' or 'Cross Section' were applied to visualise 3D air data within a virtual globe, but not in combination with a 3D city model.
- 3D web mapping APIs are preferred for the development of prototypes to visualise air data.

- Most of the used libraries are based on the programming language JS.
- `Cesium` is, beneath `ArcGIs API for JavaScript`, the most favoured 3D web mapping application API for visualising 3D spatial data.
- CityGML 2.0 [103] is the most favoured open standard exchange format for 3D city models [63].

To conduct a practical implementation of 3D air temperature data within a 3D city model following VAs were selected: (a) *point cloud* (VA_1) (b) *cross section* (VA_2) (c) *isosurface* (VA_3) (see Chapter 5).

An appropriate *visualisation application* has to fulfil following criteria: (1) state of the art in the field of 3D GIScience, (2) freely available, (3) data compatible and (4) allowing visualisation on city scale (see Section 4.1.1). Due to findings of the literature research, the defined criteria and the circumstance that the 3D city model of Vienna is based on `CesiumJS` the visualisation application `Cesium` [19], will be used to implement the VA_1. `Cesium` is according to [124] state of the art in the field of 3D GIScience, it is freely available, data compatible and allows to visualise air data on city scale. Due to technical requirements VA_2 and VA_3 will be implemented in ArcGIS Pro. ArcGIS Pro also fulfils the required criteria and, moreover, is available for free for students.

4 METHODOLOGICAL APPROACH

The following chapter gives a brief overview about the methodological approach of this master thesis. The main methodological steps and their contribution answering the research question and the subquestions will be outlined.

4.1 METHODOLOGICAL STEPS

The methodological approach of this master thesis to answer the research question can be split into the five work steps: (1) *literature research*, (2) *data acquisition*, (3) *visualisation*, (4) *evaluation* and (5) *discussion and conclusion* (see Figure 4.1).

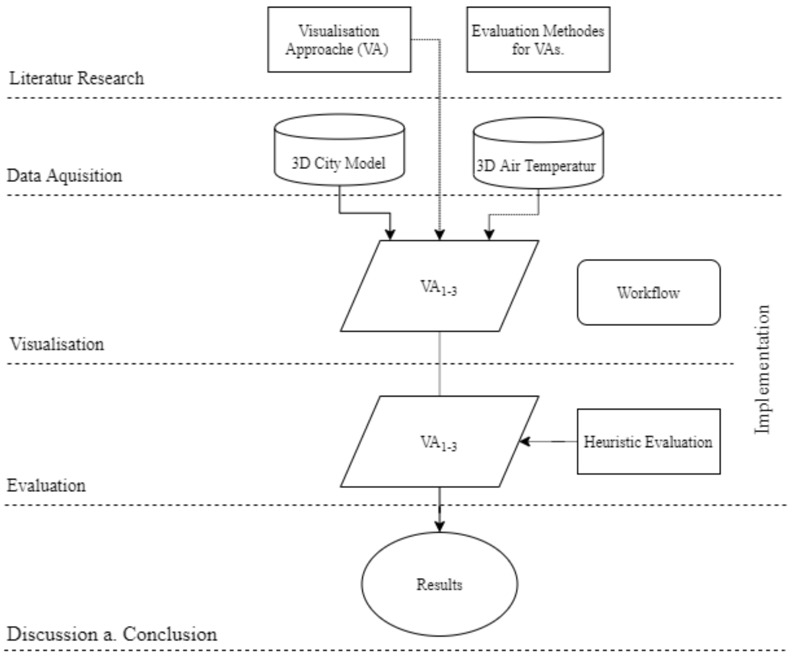


Abbildung 4.1: Flowchart of the main methodological steps of this master thesis.

4.1.1 Literature research

The superordinate goal of the literature research was to answer subquestion 1—*What are potential 3D visualisation approaches (VAs) to visualise 3D air temperature data?*—and subquestion 3—*Which evaluation method is suitable to evaluate the usability of the applied VAs?*—and to identify 3D geospatial applications, which allow to implement and visualize the VAs.

Therefore, in a first step a screening of scientific literature, journals, books, blogs as well as the identification of related work, key players and key research institutes in the field of 3D GIScience took place. The focus was on *3D geospatial VAs*, which allow the representation of 3D air temperature datasets within 3D city models and on *methods of evaluation* of the implemented VAs. The technical state of the art of 3D geospatial applications, which allow the representation of 3D air temperature data within 3D city models, was screened additionally. Requirements that were demanded of the software were: (1) state of the art in the field of 3D GIScience, (2) available, (3) integration of available data is possible and (4) allows the visualisation of 3D air temperature data on city scale.

In a second step, appropriate VAs of air data and an evaluation method were selected and described.

The key findings of the literature research are presented in Chapter 3. These findings lay the basis for the later practical implementation—the visualisation and evaluation—of the VAs implemented.

4.1.2 Data acquisition

The data acquisition was based on two meetings devoted to early stage concept presentations. Participants at the meetings were experts in the field of climate modelling, city planning and land survey coming from the Stadtvermessung Wien (MA41), Wiener Umweltschutzabteilung (MA22) and Austrian Institute of Technology (AIT), experts in the field. As a result of these presentations, the required datasets—components of the 3D city model and 3D air temperature data—were provided by these institutions.

The *3D city model dataset* had to contain a surface texture, a DTM and the 'building model'. Requirements for the data that have been requested were: (1) city scale, (2) freely available and (3) state of the art in the field of 3D GIScience. The DTM, the surface texture and the 'building model' were made available from the MA41 under terms of OGD, based on a Creative Commons Attribute 4.0 International (CC By 4.0) licence. The data sets used are described in more detail in Table 5.1.1.

The *air temperature dataset* had to (1) feature $2D + 1D, 2.5D$ or $3D$ geometric dimensions. Further requirements for the requested data were: (2) city scale and (3) highest available resolution. The air temperature dataset derived from a resampled climate model which was made available by the AIT.

4.1.3 Visualisation of the use cases

Aim of this methodological step was to answer subquestion 2—*What are main work steps to visualise 3D air temperature data within a 3D city model?*—and to deliver a workflow, as well as answer part one of the research question: *How can 3D air temperature data be visualised within a 3D city model?*.

Therefore the available datasets have been preprocessed, due to requirements of the VAs and the visualisation software (see Figure 4.2). In a further step, the preprocessed datasets have been implemented and visualised within the visualisation pipelines (see Figure 4.2). Minimum requirements which have been set for the VAs were: (1) city scale and (2) no loss of information.

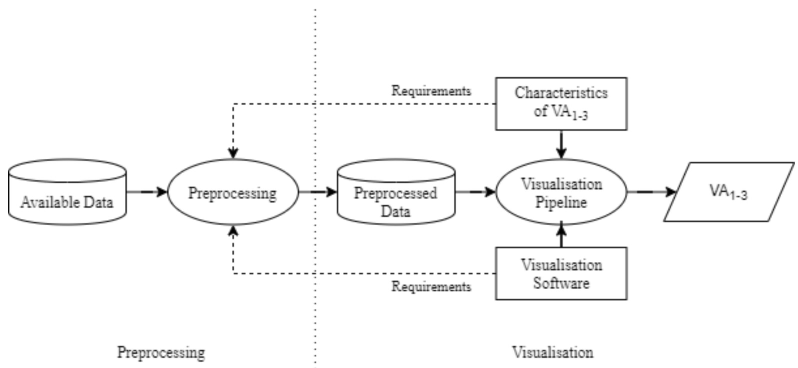


Abbildung 4.2: Preprocessing and visualisation flowchart

The implementation of the VAs was done by a heuristic approach, orientating on related work. Based on the experience of the implementation of the VAs, workflows were drained. The practical implementation and the applied software are described in detail in Chapter 5.

4.1.4 Evaluation of the visualisation approaches

Aim of this methodological step was to answer subquestion 4 and in a further step the second part of the research question: *[...] how do selected visualisation approaches perform in terms of usability?*.

Based on findings of the literature research the implemented VAs were evaluated by an Heuristic Evaluation (HE), which is an expert-based testing method. The expert-based testing method was chosen taking into account the suitability of the method to answer the research question, the time requirements for conducting the evaluation process, the technical characteristics of the implemented VAs and the COVID restrictions in place at the time of this master thesis. Special emphasis was on selecting experts in the field of 3D city modelling and 3D geovisualisation (see: Chapter 6).

The results of the expert evaluation of the VAs showed a list of usability problem (UP) for each VA, severity ratings of the UPs and further findings. The results allowed to conclude, how the implemented VAs perform in terms of usability.

4.2 CASE STUDY AREA – VIENNA

The following section describes the case study area. It gives a brief overview about its statistical key indicators, climate conditions, the state of the art of the 3D city model provided by the urban administration, the way how air temperature is visualised and which required datasets are available.

4.2.1 General overview

As case study area the city of *Vienna*, the capital of Austria was chosen. The city area extends on $414.9km^2$ and holds a population of nearly 1.9 million [74]. The population density of the study area is around 4575 inhabitant per km^2. More than 35% of the area is designated as as construction area, nearly 46% as green space, around 5% as water bodies and around 14% as traffic area [71].

There are about 200 000 buildings in Vienna. The building density is higher in the inner districts. It decreases in a ring shape from the center to the edges of the city. The situation is similar for the average height of buildings, which is located in the center of the city. The highest building—the 'Donauturm'—shows 252m [79].

4.2.2 Climate conditions

Vienna lies on the east boarder of the Alps within the 'Wiener Becken'. The 'Wiener Wald' forms the western boundary. The centre and the eastern part of the city lies on the alluvial plain of the Danube river. The lowest point of the city — with $151 m\ddot{u}A$ — is located in the 'Lobau'. The highest point within the city boundary is the 'Hermannskogel' with $543 m\ddot{u}A$.

The climate of Vienna is influenced by the marine and a humid continental climate (see Figure 4.3). The mean annual temperature for the measuring point 'Hohe Warte' in the time period 1971-2000 show 10.2°C [146]. The mean annual amount of precipitation is around $600mm$. The inner district of Vienna, with its measuring point 'Innere Stadt', show the warmest climate of Austria due to urban climate ef-

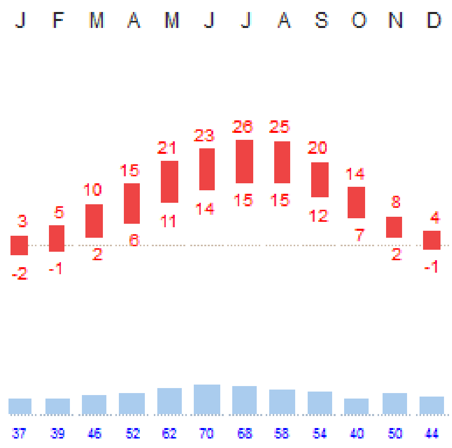


Abbildung 4.3: Climate diagram Vienna (measuring point 'Hohe Warte'; 1971-2000; 202*müA*; temperature in °*C*, rainfall in *mm*) [146].

fects. The mean annual temperature for the time period 1971-2000 lies 1.2°*C* above the mean annual temperature value of the measuring point 'Hohe Warte' [146].

In 2019 Vienna had 38 *heat days*[1] and 15 *tropical nights*[2][53]. The mean annual temperature for 2019 show 12.6°C (Hohe Warte) [53]. 2019 together with 2018 was the warmest years in measuring history.

Due to climate change a mean annual temperature increase of 2.2 to 3.8 degree for 2100, based on RCP4.5 or RCP8.5, can be assumed [119, 53]. Bastin et al. [5], based on the climate scenario RCP4.5, projects for Vienna in 2050 a climate comparable to Skopje, with an annual mean temperature value of 12.1°*C*.

To mitigate the negative effects of climate change on the inhabitants, specific measures aim to cool down the city. Therefore the city of Vienna promotes sustainable urban greening methods like facade greening, planting of trees or mobile mist showers. Projects like the '50 Grüne Häuser', the 'Sommerspritzer' or the 'Kühle Meile' can be mentioned [121]. In the last couple of years, several 2D maps were provided by the urban administration. To identify the most vulnerable areas of the city, the 'Wiener Hitzekarte'—a heat vulnerability map—which is linking social components (e. g. age of the inhabitants) and temperature, was invented in 2019 [122]. To provide further city climate informations the 'Klimaanalyse-Karte' was introduced in 2020, with the aim to support urban development processes [123].

4.2.3 3d city models of Vienna - State of the art

The main focus of this section is on the description of the state of the art of 3D city models representing the case study area. As the single example the *'Dreidimensionale Stadtmodell'*, a 3D city model of Vienna provided by the MA41, can be mentioned [78]. Solutions like Google Earth or OSM Buildings are not considered or described in this section, due to its different approach in generating input data and its accuracy.

Applied use cases

Since 2002 the Stadtvermessung Wien (MA41) runs a 3D city model of Vienna. The 3D city model supports urban planners and decision makers by modelling use cases (UCs) like visibility analysis, shadow estimation, noise propagation, pollutant dispersion or solar potential estimation [78]. But so far, no available UC is dealing with the visualisation of continuous air temperature data or air data in general, or with the visualisation of air temperature values exceeding a certain value (e. g. 25°C).

1 heat day: daily maximum temperature is above 30°*C* [73].
2 tropical night: during night the temperature does not fall under 20°*C* [53].

Components of the 3d city model of Vienna

Up to June 2021, the 3D city model of Vienna consist of a (1) DTM—the *'Digitales Geländemodell'*—, (2) a texturing map—the *'Flächen-Mehzweckkarte'*—and (3) building models—the *'Baukörpermodell'* and the *'Dachmodell'*. DTM, the texturing map and the building models—on LOD1 and LOD2—are available for the entire city area. A detailed rooftop building model on LOD3 are available for the inner districts (see Table 4.1) [75].

The DTM is derived from the 'Mehrzweckkarte'—a digital city map of Vienna—and by airborne laser scanning. The 'Flächen-Mehzweckkarte'—as surface texture—is derived from the 'Mehrzweckkarte' and shows the land use on small scale. The *'Baukörpermodell'* is drained from the (1) footprints of the 'Baukörpermodell', which were derived from the 'Mehrzweckkarte', and the (2) building height, which is detected by orthophotos. The LOD1 and LOD2 'Dachmodell' are derived from aerial image analyses. The database of these components is updated in a three-year cycle [75].

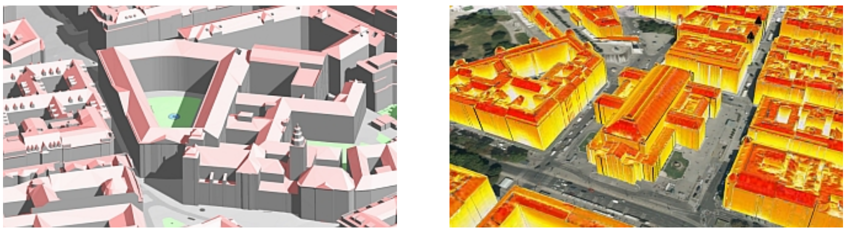
label	resolution/level of detail	available data format	amount of buildings
Digitales Geländemodell	±10 cm — ±1m	.shp; .tif; .asc; .dxf	—
Flächen-Mehrzweckkarte	few cm — few dm	.shp; .tif	—
Baukörpermodell	± 25 cm; LOD1	.shp; .dxf	ca. 200 000
Dachmodell	LOD2	.gml; .dxf	ca. 200 000
Dachmodell	LOD3	.dxf; .dwg; .xml	ca. 81 000

Tabelle 4.1: Components of the *'Dreidimensionales Stadtmodell'* of Vienna in 2018 [75].

Visualisation of the 3d city model of Vienna

Up to June 2021, the 3D city model is visualised by the application *'Stadtplan3D'* (see https://www.wien.gv.at/stadtplan3d). Following UCs are available within the Stadtplan3D: (1) shadow estimation and (2) measuring of distances. The Stadtplan3D is visualised in a browser based geospatial visualisation tool which supports the XML-based data format CityGML. The input data is managed and maintained by a commercial version of the '3DCityDB'[3] and visualised based on the CesiumJS library (see: Figure 4.4a) [78].

The *'Solarpotenzial3D Web Applikation'* is another 3D city model application provided by the MA41 with a UC focusing on solar potential estimation (see https://www.wien.gv.at/solarpotenzial3d). It is based on the same 3D city model components as the Stadtplan3D, and textures buildings based on their estimated solar potential (see: Figure 4.4b) [77].



(a) (b)

Abbildung 4.4: Comparison of current 3D city model applications of Vienna provided by the MA41: (a) 'Stadtplan3D' [78] (b) 'Solarpotenzial3D' [77].

3 3DCityDB: an open source geospatial database developed for storing, managing and representing 3D city models [63].

Applied visualisation approaches of air temperature data

The visualisation of air temperature data or air data in general is not yet a visualised UC of the 3D city model of Vienna [75, 78]. When it comes to the representation of air temperature data, 2D VAs are applied [119, 122, 145, 149]. As example the following 2D air temperature visualisation of the case study area can be shown (see: Figure 4.5).

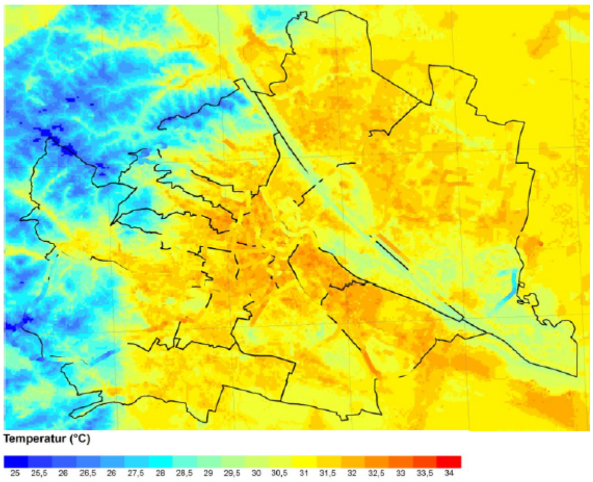


Abbildung 4.5: 2D air temperature visualisation of Vienna on July 7, 2011 based on a micro-scale model [149].

The visualised air temperature raster dataset, shown in Figure 4.5, is based on the `MUKLIMO_3` a micro-scale climate model [144]. Although the data set is featuring $2D + 1D$ geometric dimensions the visualisation is done in 2D.

Aim of this master thesis is to contribute to a further development of 3D air temperature VAs and to enrich the 3D city model with further UCs or generally spoken, to visualise potential 3D data in 3D and not in 2D.

4.2.4 Region of interest

Due to performance reasons the VAs are limited to a Region Of Interest (ROI) of the case study area (see Figure 4.6). The ROI area of 56.25 km² is based on nine DTM tiles provided by the 'Geodatenviewer' of the city of Vienna hosted by the MA41. Each tile shows a length of 2500 x 2500 m which leads to a total side length of the ROI of 7500 x 7500 m. The ROI fully covers the districts '1.Innere Stadt', '8.Josefstadt', '9.Alsergrund', and '20.Brigittenau' and parts of the 2^{nd}, 3^{rd}, 4^{th}, 6^{th}, 7^{th}, 15^{th}, 16^{th}, 17^{th}, 18^{th}, 19^{th}, 21^{th} and 22^{th} district of Vienna. The ROI represents a heterogeneous area of Vienna, differing in building density and climate conditions.

4.2.5 Data availability

All components of the *3D city model of Vienna*—the 'Dreidimensionale Stadtmodell', provided by the MA41—are freely available under terms of the Creative Commons Attribute 4.0 International (CC by 4.0) licence. Free data availability is based on the INfrastructure for SPatial InfoRmation in the European Community (INSPIRE)[4] directive and its requirement to provide government data openly [38, 120]. The data are provided by the OGD platform 'Geodatenviewer' of the city of Vienna (see `https://www.wien.gv.at/ma41datenviewer/public/start.aspx`) [76].

4 INSPIRE: an EU initiative (Directive 2007/2/EC) to establish an infrastructure for spatial information in Europe [38].

Abbildung 4.6: Case study area (Vienna) and the Region Of Interest (ROI).

As *air temperature data source*, city-scale climate models were considered, due to their spatial extension over the entire case study area and their ability to provide 3D and 4D data. Climate models of the case study area are used in the fields of urban planning, science or weather forecast and utilised by different stakeholders [25, 106, 72, 145]. Research institutes like the ZentralAnstalt für Meteorologie und Geodynamik (ZAMG) or the AIT can be listed as stakeholders which provide climate models on city-, micro- or on building-scale [2, 145]. Findings of the data research process conclude that 3D air temperature datasets of the case study area exist and were available, but they are not provided freely as OGD.

5 VISUALISATION OF 3D AIR TEMPERATURE DATA

The following sections describe the implementation of three different visualisation approaches (VAs) in the 3D city model of Vienna. In particular, the used GIS methods, tools and data sets, the necessary preprocessing steps and the implementation of the VAs are explained in detail.

5.1 USED COMPONENT MODELS OF A GIS

For the practical implementation and visualisation of the air temperature data within a 3D city model, GIS component models have been applied.

The components of a GIS can be divided into the categories *structure* of a GIS and *function* of a GIS [13]. Bill [13] introduce the four-component HSDU-model for the *structure* of a GIS and the four-component IMAP-model for the *functions* of a GIS. In this thesis these two four-component models are building the guideline for the practical implementation of the selected visualisation approaches (VA) in a 3D city model.

The HSDU-model (see: Figure 5.1) describes the structure of a GIS. It consists of the components *hardware*, *software*, *data* and *users* [13]. The structure components used in this master theses will be described in detail in the following section (see: Section 5.1.1).

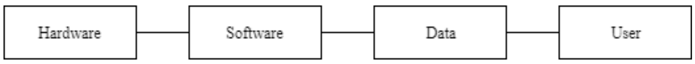


Abbildung 5.1: HSDU-model based on Bill [13].

The IMAP-model describes the function of a GIS (see: Figure 5.2). This model consist of the components *input*, *management*, *analysis* and *presentation* [13, 50]. The conducted work steps regarding the function components are described in the following sections (see: Section 5.1.2).

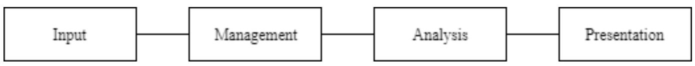


Abbildung 5.2: IMAP-model based on Bill [13].

5.1.1 Used HSDU-components

Hardware

The data processing, the implementation of the VAs in the 3D city model of Vienna, as well as the following evaluation procedure was done on a personal computer consisting of 16 AMD Ryzen 7 PRO 4750U with Radeon Graphics 1.70 GHz, 32 GB RAM, a 64-bit central processing unit running Windows 10 Pro (see Table 5.1).

Component	
Processor	16 AMD Ryzen 7 Pro 4750U with Radeon Graphics 1.70 GHz
Random-Access Memory (RAM)	32 GB
Central processing unit (CPU)	64-bit
Operating system	Windows 10 Pro

Tabelle 5.1: Used hardware components.

Software, libraries and script language

For the preprocessing of the air temperature dataset and the visualisation of the selected VAs, different software was used:

JavaScript (JS) is a script language mainly used for dynamic HTML in web-browsers. The JS programming language was used in the context of the implementation of VA_1 in `Cesium Sandcastle`, a live code editor and example gallery [20].

FME is a feature manipulation and data conversion engine. The FME Desktop Versions 2020.0.2.1—2020.1.1.1 for Windows were used for the preprocessing of the air temperature data implemented in the 3D city model by VA_1. Used components of the engine were the 'workbench' and the 'data inspector'.

ArcMap is a Geographical Information System (GIS) software application which allows data manipulation, analysis and visualisation in 2D. ArcMap 10.7.1 was used for data preprocessing and transformation processes. Following extensions of the GIS software were used: '3D Analyst', 'Data Interoperability', 'Geostatistical Analyst', 'Spatial Analyst'.

ArcGIS Pro is a single Geographical Information System (GIS) application which supports the data visualisation in 2D, 3D and 4D. ArcGIS Pro 2.6.3 was used for data transformation, to visualise VA_2 and VA_3 and to conduct parts of the Heuristic Evaluation (HE).

CesiumJS is an open source JS library, released under terms of Apache License 2.0, which allows to create 3D globes and to share dynamic geospatial data within interactive web apps. In the scope of this master thesis version 1.69 was applied.

CesiumIon is an end-to-end cloud platform and 3D geospatial application—based on CesiumJS—which allows to tile, host and visualize geospatial data over the web [19]. CesiumIon also provides 3D content. The application is based on WebGL and JS. In the context of this master thesis a free community account was used. Detailed information about the stetting of the free community account is given in Table 5.2. Used 3D content provided in the 'asset depot' of CesiumIon is described in Table 5.1.1.

apps a. end users	storage	data streaming	bing maps sessions
no limit	5 GB	15 GB p.m.	1000 p.m.

Tabelle 5.2: selected parameters of the *community account* of CesiumIon.

Integrated into the CesiumIon platform is *Cesium Stories*, which allows to build and share 3D geospatial presentations and stories on the web. Cesium Stories was used to visualise VA_1 and to conduct parts of the Heuristic Evaluation (HE).

Data base

3d city model dataset

The dataset of the 3D city model of the ROI was inspired by the *'Dreidimensionales Stadtmodell'* of Vienna . The three main components of the 3D city model are (1) the building model, (2) the DTM and (3) the surface texture (see Figure 5.3).

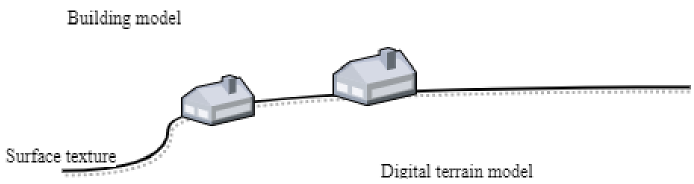


Abbildung 5.3: Components of a 3d city model.

The three components of the applied 3D city model, namely 'Generalisiertes Dachmodell', 'Geländemodell' and 'Orthofoto' were provided by the MA41 (see Datenquelle: Stadt Wien - data.wien.gv.at) under terms of CC BY 4.0. The 'Geländemodell' resembles the DTM, 'Generalisiertes Dachmodell' resembles the building model and 'Orthofoto' and 'Bing map' resemble the surface texture (see Table 5.3) The reference system of all three components is based on the 'Landeskoordinatensystem Gauß-Krüger M34' with the Euopean Petoleum Survey group Geodesy (EPSG)-code 31256. The heights given refer to *'Wiener Null'*—156.68m above Adriatic sea and the EPSG-code 1267. Unlike the reference system the components differ in terms of resolution/LOD, data format, spatial extent of the tiles and actuality (see: Table 5.3).

Component	Label	Resolution/LOD	Data format	EPSG-code
DTM	Geländemodell	±10 cm — ±1m	.tif; .asc	31256
Building model	Generalisiertes Dachmodell	LOD2	.gml;	31256; 1267
Surface textures	Orthofoto	±15 cm	.jpg	31256
	Bing Map	few cm — few dm	—	3857

Tabelle 5.3: Components of the 3D city model [75] .

The *building model* also covers the entire case study area in LOD2. It is based on orthophotos dated 2013. The building model data set is split into 1460 500 x 500m tiles and obtained in the data format .gml, which is based on the open data model CityGML 2.0 [76].

The *Digital Terrain Model (DTM)* covers the entire case study area. The spatial resolution within the dataset ranges from 10 cm to 1 m due to different survey procedures. It is based on information dated 2017 and prior. Bridges are not featured within the data set. To easy data handling the DTM data set is split into 98 2500 x 2500 m tiles and obtained in the data format .tif [76].

The *surface texture* used in ArcGIS Pro to show VA_2 and VA_3 bases on the 'Luftbilder' dated 2019. The 'Lufbilder' are split into 2500 x 2500 m tiles with a spatial resolution of 15 cm. The obtained data format is .jpeg [76]. The *surface texturing* used in CesiumIon to show VA_1 bases on the Bing Map provided by CesiumIon [19].

Air temperature dataset

Beside the three components of the 3D city model described above, the air temperature dataset can be seen as the fourth component visualised in the 3D city model of the ROI (see Figure 5.4).

The used air temperature dataset was drained from a resampled regional climate model which was made available by the 'Competence Unit - Digital Resilient Cities' of the AIT. As mentioned before, the advantage of this air temperature dataset drained form a regional climate model is, that (1) covers the entire case study area and

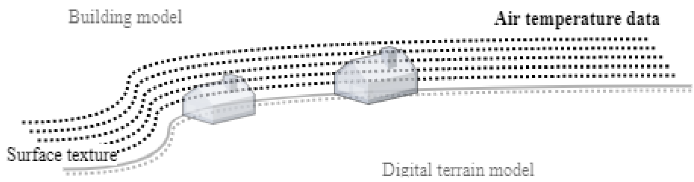


Abbildung 5.4: Additionally visualised air temperature data within a 3d city model [own figure].

(2) features $2D + 1D$ geometric dimensions. In contrast, data sources on micro-scale level provide higher spatial resolution but are not covering the whole case study area or at least the ROI. The chosen air temperature dataset consists of five different layers. Layer 1 to Layer 5 features the z-values 2 m, 10 m, 34.5 m, 69 m and 119 m above earth surface. Each layer has a spatial resolution of about 1000 x 1000 m and shows the air temperature data on the 30.07.2016 at 00:00 as an attribute value. The data is provided in the .adf data format (see Table 5.4).

Layer	z-value in m	Time res.	Spatial res. (x,y) in km	Data format	EPSG-code
1 — 5	2, 10, 34.5, 69 and 119	hourly	1, 1	.adf	4326

Tabelle 5.4: Parameters of the *'resampled CCML'* of Vienna [own figure].

The spatial resolution of about 1000 x 1000 m is a limitation of this dataset. Due to this fact, the air temperature data values are interpolated during the implementation process to gain spatial resolution of the air temperature (see: Section 5.2.1 and Section 5.3.1).

Users, use cases and spatial operations

As described in Chapter 2, 3D city models are used—besides other reasons—to support decision-making and monitoring processes. Therefore potential users of a 3D city model showing UCs dealing with air temperature visualisation are in the scope of planning procedures and citizen participation political *decision-makers*, *urban planners* and *civil society* [12, 48].

In the scope of this master thesis two Use Cases (UCs) were applied due to different visualisation characteristics of the implemented VAs. UC_1 deals with the continuous visualisation of the air temperature values. UC_2 deals with the visualisation of air temperature values exceeding a certain value (e. g. 25°C). VA_1 allows to visualise UC_1 and UC_2. VA_2 is able to visualise UC_1 and VA_3 is able to visualise UC_2 (see Table 5.5).

Applied Visualisation Approach (VA)	Applied Use Case (UC)
VA_1	UC_1 and UC_2
VA_2	UC_1
VA_3	UC_2

Tabelle 5.5: VAs and their applied UCs [own figure].

The used VAs allow several spatial operations like the identification of clusters (e. g. UHI), relationships, the overstepping of defined temperature values or the identification of temperature values in general.

5.1.2 Applied IMAP-components

In a first step the *input-*, *management-*, *analysis-* and *presentation-*components of the IMAP-model of a GIS are described and related to this master thesis. In a second step the four components of the IMAP model will be set in context to the applied web 3D GIS applications Cesium.

Applied IMAP-components regarding GIS in general

The component *input* describes the data acquisition or measuring method, which differ in terms of cost and quality [13]. These input data are provided by *authoritative* or *asserted* data sources. According to Harvey and Leung [50] currently data streams shift from authoritative data sources to *asserted* data sources. Authoritative data sources are for example national mapping agencies (e. g. MA41), which capture data actively by various cartographic and land surveying techniques. Asserted data sources or 'volunteered geographic data' are generated as a by-product of collaborative volunteer efforts from location enable devices. Google Maps for Mobile can be mentioned as an example for asserted data sources [50]. In 2007 Goodchild [45] therefore coined the term 'citizens as sensors' and claims that citizens as sensors became the primary input mechanism.

In the scope of the master thesis only authoritative data source were used. Nevertheless, the utilization of asserted data sources within 3D city models is discussed in Chapter 7.

The management and modelling of data is described within the IMAP-model component *management*. A GIS requires database management functions to facilitate the storage, organization and retrieval of user contributions [50]. An important aspect is the applicability of the data type. Suitable data types (vector, raster or attribute data) are determined by access speed and data volume on the data management side [13].

The core of the software part for the management of spatial data is the Geographical DataBase (GeoDB) with its corresponding DataBase Management System (DBMS). They GeoDB construction differs regarding its nature (e. g. dynamic, real-time, etc.) and purpose (e. g. emergency management). The DBMS organizes the underlying data regarding their geometry, topology, attribute, temporal and metadata. The data models of the DBMS can be either a relational or an object-oriented model [13].

The raw data which was provided for the visualisation of 3D air temperature data in this thesis was initially not applicable in terms of data types. Therefore several preprocessing steps had to be conducted to convert the datasets in applicability data types (see Section 5.2.1 and Section 5.3.1). Detailed information about the applied GeoDBs, DBMS and data models were shown in the following section (see: Section 5.1.2).

The *analysis* is a further component of the IMAP-model. Goodchild [46] highlights the analytical functions of GIS as one of its main strength. Bill [13] understands analysis to be the scientific research of a situation taking into account its partial aspects or rather the fragmentation of a whole into its parts. As a result new information is gained [13].

A distinction can be made between *qualitative* and *quantitative analyses*. Qualitative analysis examines the nature and the characteristic of the problem, while quantitative analysis examines the amount and the size of the phenomena that occur [13].

Different methods are used for data analysis. These methods are based on mathematical principles and range from *geometrical*, *logical* and *relational* correlation of data to *statistical procedures*. The algorithm can therefore be grouped according to geometry, topology, subject matter and dynamics [13]. As examples of relevant analysis methods in GIS, time series analyses, network analyses, boolean algebra[1] or multiple-criteria decision analysis can be listed [13]. In the scope of this master thesis, the interpolation of the air temperature values, to gain a higher spatial resolution of the datasets, can be stated as conducted analysis function (see: Section 5.2.1

1 boolean algebra—truth values (true and false) are the variables of this branch of algebra [44].

and Section 5.3.1).

The IMAP model component *presentation* is dealing with the *geovisualisation* of the results based on methods of cartography and computer graphics [13]. According to Bill [13], graphical representation facilitates the presentation of results and increases the acceptance of a GIS by its user. Beside cartographic products, geovisualisation includes various other forms of representation like multimedia presentations, fly through, virtual reality and augmented reality Bill [13]. In the scope of this master thesis, the visualisation of the air temperature datasets—based on different VAs—was done in the Graphical User Interface (GUI) of Cesium Stories and ArcGIS Pro (see: Section 5.2.2 and Section 5.3.2).

Applied IMAP-components regarding web 3D GIS

Parts of the implementation of VA_1 was conducted in a web 3D GIS application. Web 3D GIS covers a GIS workflow within a web environment [13]. As described before, a GIS workflow is based on the principles of data input, management, analysis and presentation (see Figure 5.2). Within a web 3D GIS, these principles are implemented with the web components *client*, *DBMS*, *GIS libraries* and a web server. The communication between the components is realised by the web server. Different standards (e. g. OGC specifications) support the handling of the geospatial data [52]. Table 5.6 shows the four GIS principles and their corresponding web components.

GIS principle	Web component
Data input	Client
Data management	DBMS with a spatial component
Data analysis	GIS library
Data representation	Client/server

Tabelle 5.6: GIS principles and their corresponding web component Held et al. [52].

The minimum system architecture of a web GIS consists of the components client, server and spatial database (see Figure 5.5). The *client* is a stand-alone or a browser-based application communicating with the server through a standard web protocol (e. g. Hypertest Transfer Protocol (HTTP)). In order to view and interact with the data, browsers often require an adequate plug-in[2]. The *web server* has to deal with requests from the client. It also has to communicate with the server side *GIS components* (software libraries) to do analyses. Server side components are furthermore responsible for the connection of the *spatial database*. Spatial databases and their management systems DBMS are required to manage 3d spatial data [52].

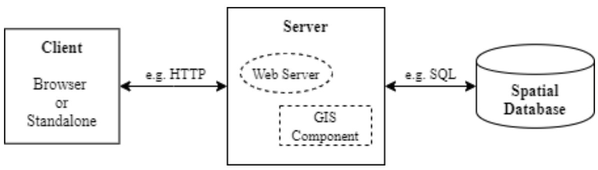


Abbildung 5.5: minimum Web GIS architecture [52].

The applied web 3D GIS application Cesium—to show VA_1—is a browser-based application. To run this application no plug-in is needed. CesiumJS functions as 3D GIS library on server side (see: Section 5.2).

2 plug-in: an optional software component which adds a specific feature to an existing software [13].

5.2 IMPLEMENTATION OF POINT CLOUDS (VA_1)

According to the findings of the literature research (see Chapter 3) the visualisation approach 'point cloud' based on `CesiumJS` was chosen as VA_1. The point visualisation was accomplished by the use of 2D billboards.

To create VA_1 a heuristic approach was applied. Related work and showcases like Cesium GS, Inc. [20], Chow [22], Poulain [107] or Stahre Wästberg et al. [125]—beneath others—were used as guideline and inspiration. Aim of this section is to describe necessary data preprocessing steps and how the data is visualised in Cesium Stories. Also the section aims to deliver a workflow to reproduce the results.

5.2.1 Data preprocessing

To accomplish the visualisation of the four components air temperature, building model, DTM and surface texture in Cesium Stories various preprocessing steps have to be applied. The raw data preprocessing was necessary due to different reference systems, low spatial resolution or incompatibility of the available data format with Cesium Stories. The preprocessing of data for VA_1 was done by using ArcMap 10.7.1 and FME Desktop 2020.1.1.1

Air temperature data

The air temperature dataset needed to be preprocessed to rise the spatial resolution, to transform the data format into a data format which can be processed in Cesium Ion and to merge layer$^{1-5}$ into one layer with 3D air temperature data. The preprocessing workflow of the air temperature dataset is structured as shown in Figure 5.6.

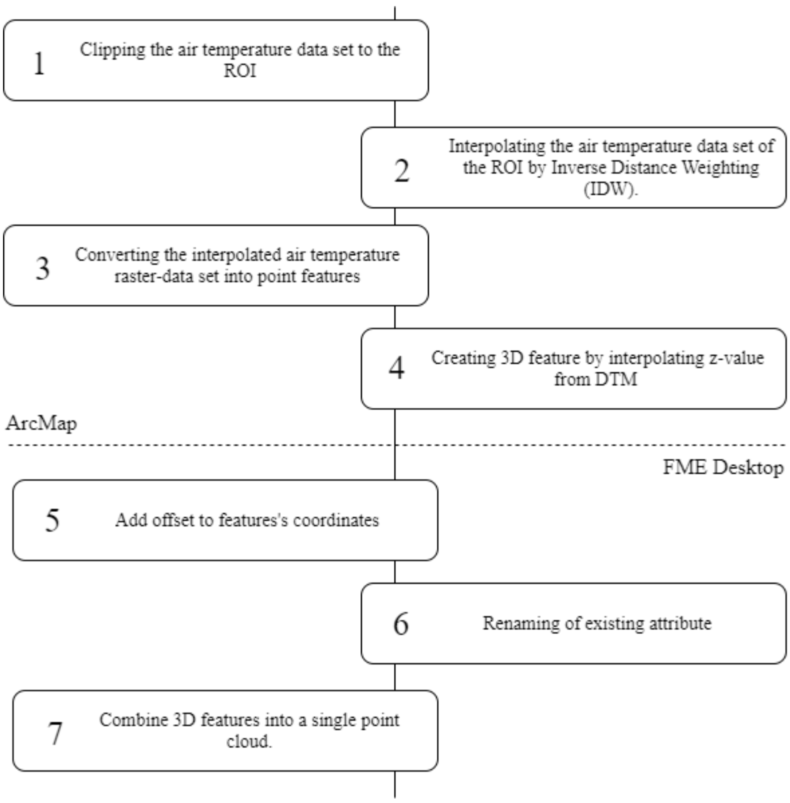


Abbildung 5.6: Preprocessing workflow of the air temperature data set in VA_1.

First the air temperature dataset has to be clipped to the ROI. This work step was done, when the layer$^{1-5}$ raster data sets were loaded into a GeoDB by using the tool

' Raster To Geodatabase (multiple)'. In the environment settings 'Processing Extent' therefore the DTM of the ROI defines the extent.

Secondly, to raise the spatial resolution of the clipped air temperature datasets of layer$^{1-5}$, they had to be interpolated. The interpolation was done by the 'Geostatical Wizard' applying the interpolation method Inverse Distance Weighting (IDW). IDW is an exact and quick deterministic interpolator [32]. This method obtains robust results when the sampling is sufficiently dense, which is the case. The spatial resolution thereby could be increased from 0°0'36"(1.112 m) to around 0°0'1"(30.9 m) Interpolated air temperature raster datasets were created by the tool 'GA Layer To Grid'.

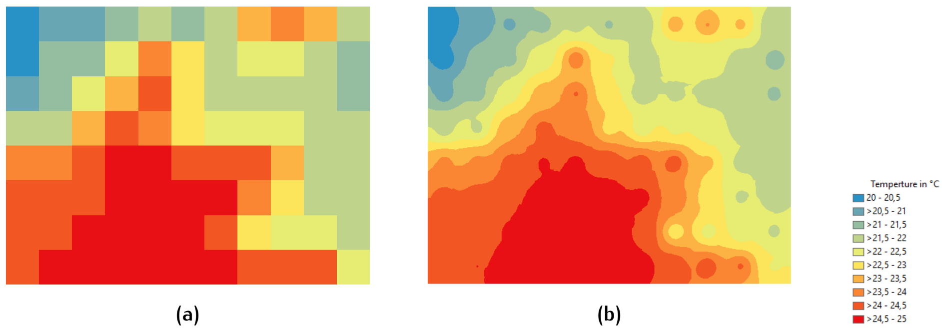


Abbildung 5.7: Increasing the spatial resolution of the air temperature raw data of the *regional climate model* (a) by implementing the interpolation method *Inverse Distance Weighting* (b).

Thirdly, the interpolated air temperature raster datasets were converted into point features. The operation was done with the tool 'Raster to Point'. The 'XY Resloution' was set with 50 m within the 'Environment Setting'.

In the fourth step 2D point features were enriched with height information to create 3D point features by interpolating z-values from the DTM. This operation was processed with the tool 'Interpolate Shape' and allows to label the air temperature data subsequently 3D air temperature data. Following the interpolation the 3D air temperature point features were converted from the GeoDB feature class to a shapefile (.shp) to allow further preprocessing steps in FME Desktop.

In the Workbench of the FME Desktop the offsets of layer$^{1-5}$ had to be added to the features coordinates (see: Figure 5.8). This operation was done with the transformer 'Offsetter' for each layer.

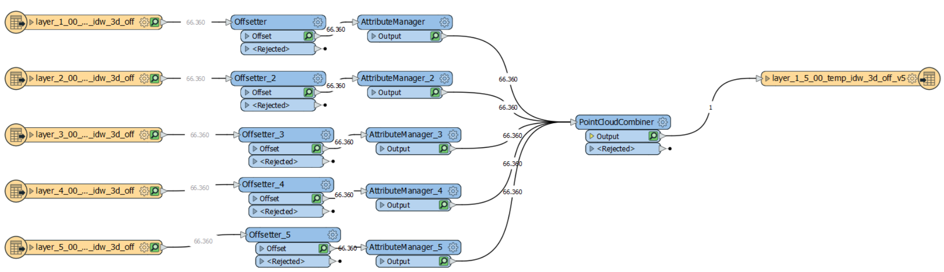


Abbildung 5.8: Preprocessing steps of VA_1 conducted in FME Desktop Workbench.

In the sixth step the attribute fields 'GRID_CODE' of the off-setted 3D air temperature point features have to be renamed into 'classification' due to data format limitations of the finally created LAS file (.las).

As seventh work step the 3D point features still separated in layer$^{1-5}$ were combined into a single point cloud. This operation was done with the transformer 'PointCloudCombiner' and finally written as LAS file (.las)

Building model

To integrate the building model of the ROI into CesiumIon, 223 tiles, with a length of $500x500m$ and stored in the GML data format (.gml), had to be compressed into a ZIP file (.zip). No further preprocessing steps were necessary to guarantee a proper visualisation in Cesium Stories.

Digital terrain model

The DTM raw data set of VA_1 was provided by the MA41 under terms of CC BY 4.0 in 25000x2500m tiles based on the spatial reference system 'Landeskoordinatensystem Gauß-Krüger M34' (EPSG-code 31256). To harmonize the DTM dataset with the other components of the 3D city model and to allow the visualisation in Cesium Stories two preprocessing steps have to be performed in ArcMap (see: Figure 5.9).

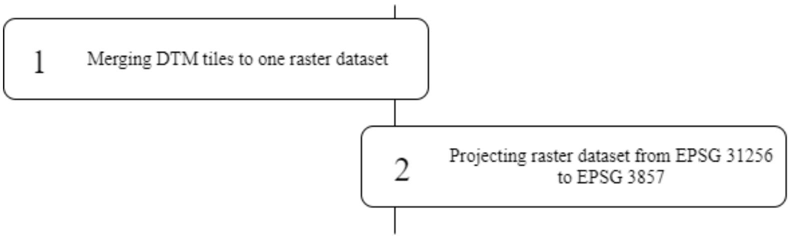


Abbildung 5.9: Preprocessing workflow of the DTM in VA_1.

For the visualisation of the VA_1 in Cesium Story the DTM tiles had to be merged in a first step. This process was done by using the tool 'Mosaic To New Raster'. Nine tiles were merged to one single raster data set covering the ROI.

Due to circumstance that Bing Maps Aerial is used as surface texture of VA_1, which is based on 'Web Mercator Projection' (EPSG-code 3857), the DTM of ROI has to be projected to harmonize the data sets. The projection was therefore done with the tool 'Project Raster'.

Surface texture

Bing Maps Aerial was used as surface texture for 3D city model of the VA_1 provided by CesiumIon. Bing Maps Aerial is based on 'Web Mercator Projection' (EPSG-code 3857), therefore no further preprocessing steps were necessary.

5.2.2 Visualisation of VA_1 in Cesium Stories

VA_1 was visualised in Cesium Stories. Therefore the preprocessed datasets of air temperature data, building model and DTM had to be integrated in CesiumIon. The integration of the datasets has been done in 'My Assets' with the function 'Add Data'. The DTM was defined as 'Raster Terrain'. The terrain options for 'Height unit' were set on 'Meters', the 'Height reference' on 'Ellipsoid(WGS84)' (see: Figure 5.10).

The building model was defined as CityGML data format. CesiumIon allows to set further CityGML Options like 'Draco Compression', which creates a smaller tileset influencing the streaming performance. Colour and texture settings as well as the function 'Clamp to terrain' were not implemented (see Figure 5.11 (a)).

The 3D air temperature dataset was defined as 'Point Cloud' and added in the LAS data format (.las). To increase the streaming performance of the dataset the function 'Draco Compression' was enabled (see Figure 5.11 (b)).

In the next step the integrated datasets were visualised in Cesium Stories, an interactive 3D presentation tool in CesiumIon. Therefore a 'New story' had to be created and the datasets to be visualised were selected via 'Add Assets'. CesiumIon

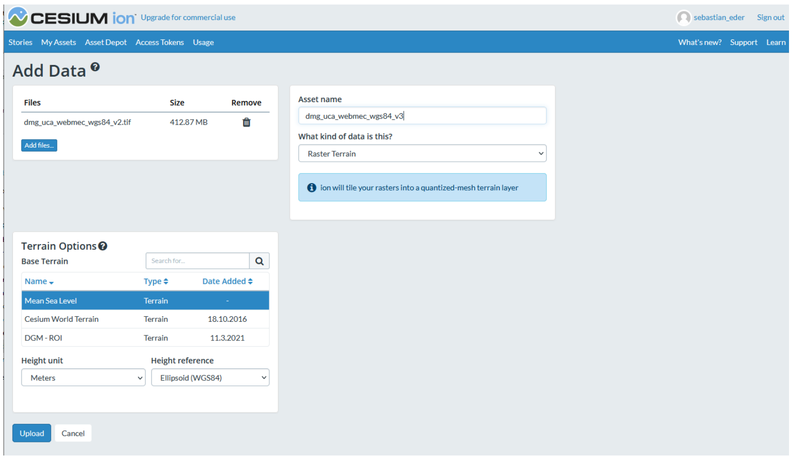
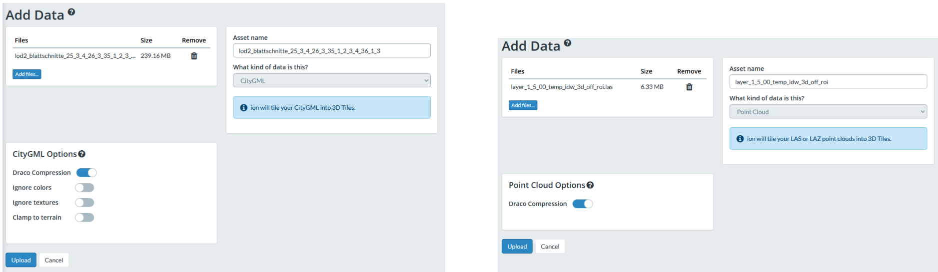


Abbildung 5.10: Adding the DTM of the ROI to CesiumIon.



(a) (b)

Abbildung 5.11: Adding (a) the building model and (b) the 3D air temperature dataset of the ROI to CesiumIon.

uses the term 'assets' for added datasets. As underlying terrain of the scene the DTM of the ROI had to be selected (see Figure 5.12).

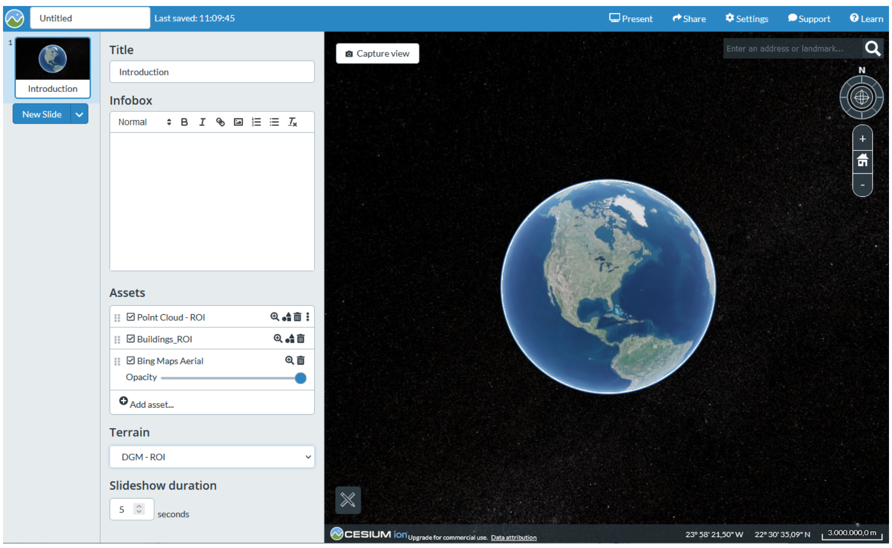
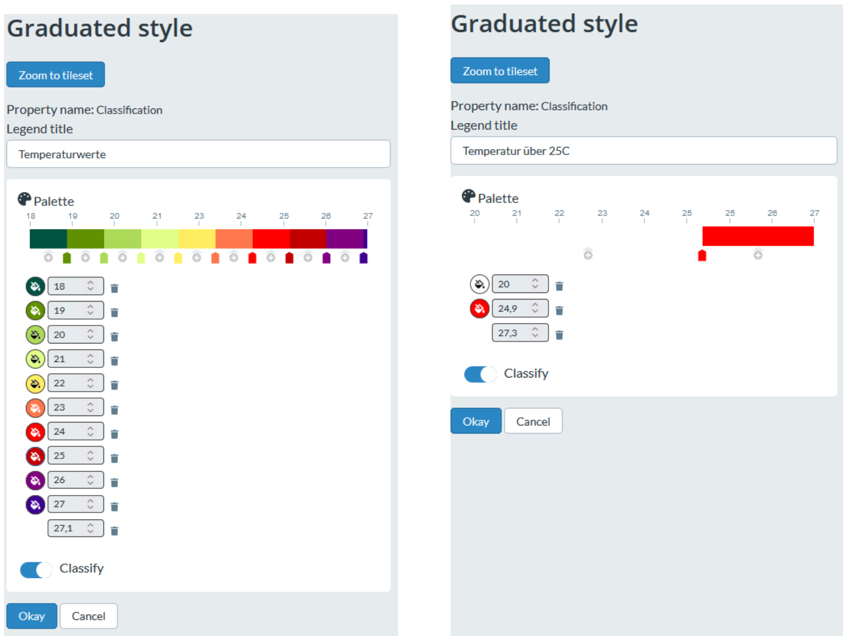


Abbildung 5.12: Creating a 'New Story' in Cesium Stories

The style of the assets can be edited with the function 'Edit style'. This function allows to classify the colour of the 3D air temperature dataset based on the attribute value 'Classification'. As indicated in Section 4.2 for the visualisation, two Use Cases (UCs) have been created. UC_1 represents continuous 3D air temperate data. UC_2 visualises 3D air temperature values exceeding a certain value (e. g. 25°C). To create

UC_1 and UC_2 the air temperature data set was visualised in two different styles (see: Figure 5.13). In UC_1 for the temperature range 18°C to 27°C each temperature increase of 1°C owns an unique colour value in graduated style of the legend. In UC_2 the air temperatures values above 24.9°C show a different colour value than the air temperature values beneath 24.9°C.



(a) (b)

Abbildung 5.13: Graduated style of the 3D air temperature dataset depending on the UC to visualise: (a) UC_1 and (b) UC_2.

As final step for each slide of the story, created in Cesium Stories, a content of the 'Infobox' was created to ease the Heuristic Evaluation (HE) of VA_1. The infoboxes subsequently contain information about the visualised datasets, and the given tasks. Also, the infoboxes include questions to guide the HE. For the HE, the web-scene of VA_1 was shared as Uniform Resource Locator (URL) and ran browser-based.

5.3 IMPLEMENTATION OF CROSS SECTIONS (VA_2)

According to the findings of the literature research (see Chapter 3) the visualisation approach *sections*, visualised in the 'Viewer Window' of `ArcGIS Pro`, was chosen as VA_2. A 'section' can be defined as two-sided vertical or horizontal plane cutting through a voxel layer [36]. Aim of this chapter is to describe the data preprocessing steps and the their implementation process to enable the visualisation of 'Cross Sections' in the Scene Viewer. VA_2 only allows to apply UC_1. To implement the VA_2, tutorials and documentation provided in ArcGIS Pro were drawn to assistance and used as guideline ([36]).

5.3.1 Data preprocessing

The following section describes the raw data preprocessing of the four components air temperature, building model, DTM and surface texture, which allows to visualise these components as local scene in ArcGIS Pro. The preprocessing steps had to be done due to implementation requirements (e. g. GML data format is not directly supported). The preprocessed datasets were used to visualise VA_2 and VA_3.

Air temperature data

Aim of the air temperature data preprocessing is to generate a voxel layer, which allows to visualise the 3D air temperature of the ROI in the 'Viewer Window' of ArcGIS Pro Section 5.3.2. As input dataset the interpolated 2D point features created in work step 3 of the air temperature data preprocessing in VA_1 were used. The data preprocessing was done in ArcMap 10.7.1 and ArcGIS Pro 2.6.3 and is shown in Figure 5.14.

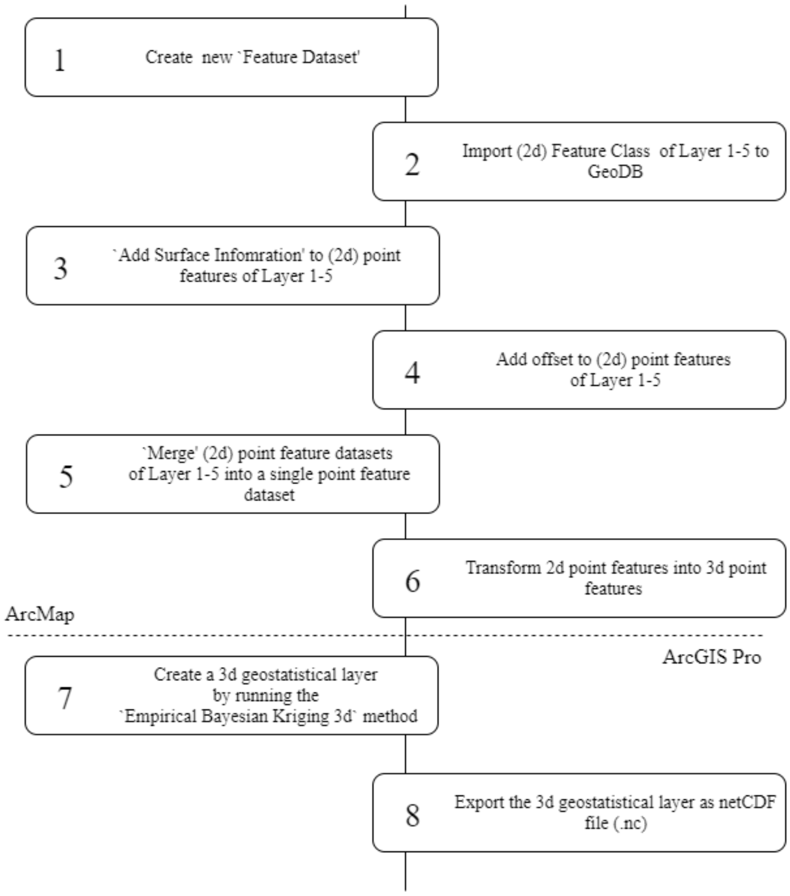


Abbildung 5.14: Preprocessing workflow of the air temperature data in VA_2.

As first step to provide all features in consistent coordinate systems, a 'New Feature Dataset' was created. The XY coordinate system was set to EPSG:31256, the coordinate system used for the Z-coordinates was set to EPSG:5195.

Secondly, the 2D point feature classes of $layer^{1-5}$, created in work step 3 of the air temperature data preprocessing in VA_1 (see Section 5.2.1), were imported into the previously defined GeoDB. The integration was done with the tool 'Feature Class to Geodatabase (multiple)'.

The next work step deals with the addition of the surface information derived from the DTM to the point features of each layer. This process was accomplished with the tool 'Add Surface Information'.

Fourthly, the offsets of $layer^{1-5}$—2m, 10m, 34.5m, 69m and 119m— had to be added to the point features. Therefore the offset values were calculated to the z-value of each point feature by using the tool 'Calculate Field'.

Work step five combines the input point feature datasets of the $layer^{1-5}$ into a single output dataset. This process was performed with the tool 'Merge'.

In work step six, 3D point features were created by using the height values derived form the 'Z'-attribute of the previously processed point feature class. This preprocessing work step was conducted with the tool 'Feature To 3d By Attribute'.

Seventh, the 3D point features were interpolated with the 'Empirical Bayesian Kriging 3D' method to create a 3D geostatistical layer. Empirical Bayesian Kriging 3D is a geostatistical interpolation method to interpolate 3D point data [37]. 3D geostatiscital layers predict values at any location within the 3D layer [34]. This operation was done with the geostatistical analyst tool 'Empirical Bayesian Kriging 3D' in ArcGIS Pro.

To prepare the visualisation of the 3D geostatistical layer as a voxel layer in a local scene, the previously created 3D geostatistical layer had to be exported as netCDF file (.nc). This process was done with the geostatistical analyst tool 'GA Layer 3D To NetCDF'.

Building model

The raw dataset of the buidling model of VA$_2$ was provided in 500x500m tiles as CityGML file (.gml). The direct integration of CityGML files in ArcGIS Pro 2.6.3 is not possible and a workaround is required. This workaround bases on a provided Toolbox, which allows to transform the CityGML files into a Scene Layer Package (SLPK) files [143]. A SLPK is a file format for scene layers, which stores, publishes and allows to read 3D datasets Environmental Systems Research Institute, Inc. (Esri) [30]. The geoprocessing tool 'Convert Building From CityGML' is based on the 'Data Interoperability' extension for ArcGIS Pro and uses a FME Workbench [143].

To view the building model of the ROI, in ArcGIS Pro the toolbox 'CityGML-toi3s.tbx' has to be added, the tool 'Convert Building From CityGML' has to be run and the selected building dataset has to be converted to a SLPK file (see:). For detailed information who to implement the toolbox and run the tool Wittner [143] can be recommended.

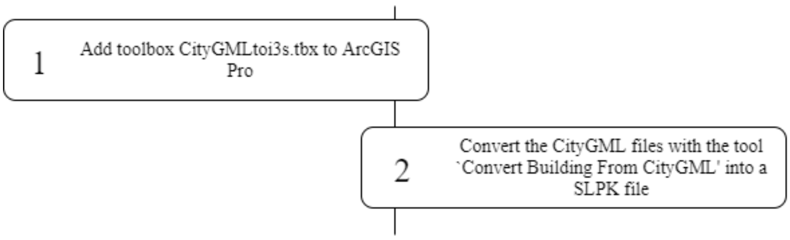


Abbildung 5.15: Preprocessing workflow of the building model in VA$_2$.

Digital terrain model

The raw dataset of the DTM of VA$_2$ was provided in 25000x2500m tiles. The dataset is also lacking the 'Spatial Reference XY Coordinate System' attribute value 'Datum'. The DTM used in VA$_2$ has to cover the ROI and has to have the same spatial references as the local scene.

Due to this requirements, the DTM dataset of VA$_2$ has to be merged to a new raster dataset. This process was done by using the tool 'Mosaic To New Raster' in ArcGIS Pro. Within this geoprocessing tool the spatial reference for the new raster dataset can be defined additionally by aligning the 'Spatial Reference for Raster' to 'Current Map' (see: Figure 5.16).

Surface texture

The raw dataset of the surface texture of VA$_2$ was provided in 25000x2500m tiles. The dataset is also lacking spatial reference information. The surface texture used in VA$_2$ has to cover the ROI and has to have the same spatial reference as the local scene.

Due to this two requirements, the surface texture dataset of VA$_2$ was merged to a single raster. This process was done in ArcMap by using the tool 'Mosaic To

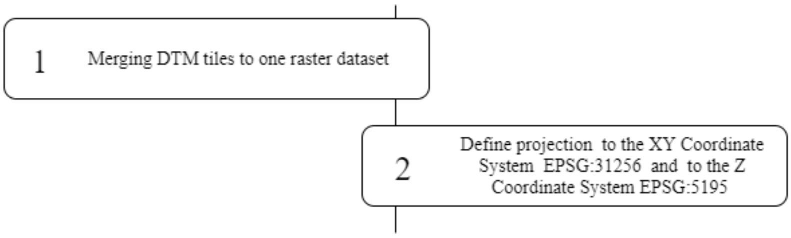


Abbildung 5.16: Preprocessing workflow of the DTM in VA2.

New Raster'. To allow a projection of the dataset its coordinate system has to be specified. Therefore the definition of the coordinate system in EPSG:31256 was done by applying the tool 'Define Projection' (see Figure 5.17).

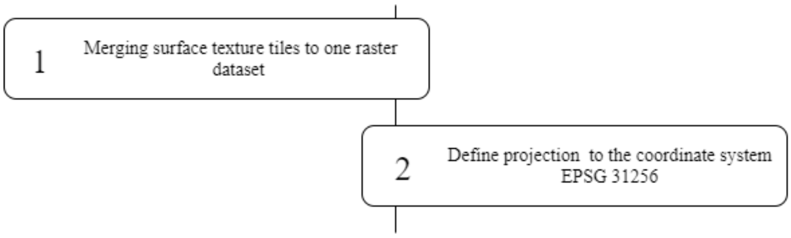


Abbildung 5.17: Preprocessing workflow of the surface texture in VA2.

5.3.2 Visualisation of VA2 in ArcGIS Pro

Due to licence restrictions, regarding the voxel layer representing the air temperature data, VA2 could not be shared as web scene. Therefore VA2 was visualised in the 'Scene Window' of ArcGIS Pro (see: Figure 5.18).

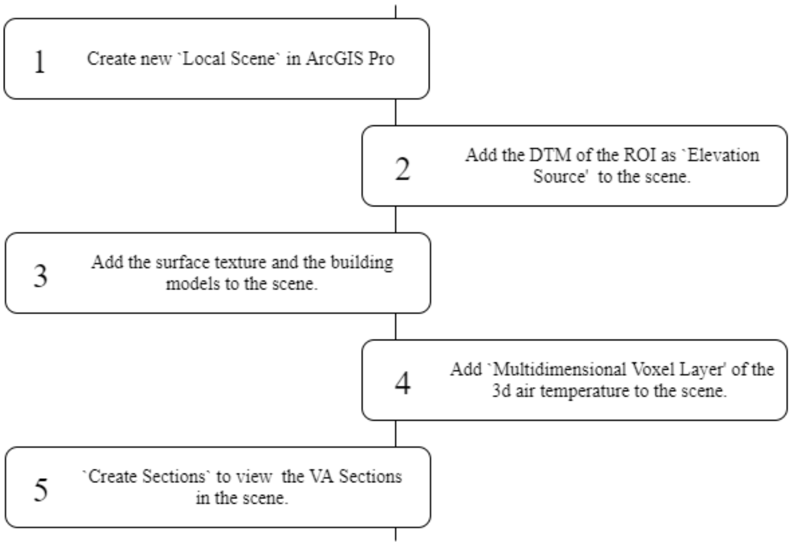


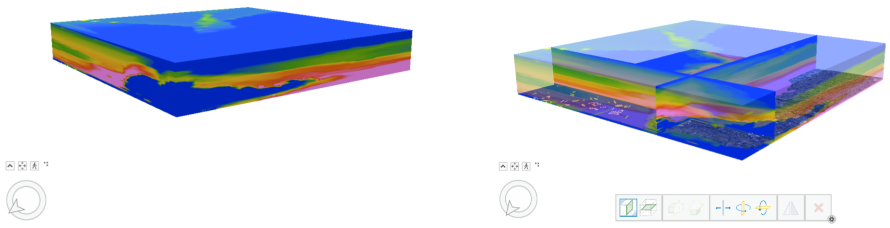
Abbildung 5.18: Visualisation workflow of the VA2.

The previously preprocessed datasets of the air temperature, the building models, the DTM and the surface texture had to be added to a new 'Local Scene'. The DTM of the ROI was added to the local scene with the function 'Add data—Elevation Source'. The surface texture available as raster file (.tif) and the building models available as layer package file (.slpk) were implemented with the tool 'Add Data'.

To view the voxel layer of the 3D air temperature data, available as netCDF file (.nc), in the 'Local Scene', the dataset has to be added with the function 'Add Data—

Multidimensional Voxel Layer'. The 'Data Type' has to be set to 'Continuous'. It is important to mention that the voxel layer can only be drawn in a local scene with the same coordinate system as the voxel layer.

Voxel layers can be shown as *volume* or as *surfaces* (see Figure 5.19). The category surfaces can further be divided in *sections* and *isosurfaces* which were applied as VA_2 and VA_3 in this master thesis.



(a) (b)

Abbildung 5.19: Visualising options of voxel layers (a) Volume or as (b) Sections VA_2.

To visualise the air temperature data in VA_2, Sections have to be created with the function 'Create Section'. In the scope of this master thesis three sections—running from (1) north to south, from (2) east to west and (3) horizontally—were created within the local scene (see: Figure 5.22). Default settings of the software solution regarding the colour range or transparency were not changed.

5.4 IMPLEMENTATION OF AN ISOSURFACE (VA_3)

Based on the findings of the literature research (see Chapter 3) the visualisation approach *isosurface* visualised in the 'Viewer Windows' of `ArcGIS Pro` was chosen as VA_3. An isosurface can be described as a surface representing a defined value within a continuous variable [33]. Aim of this section is to describe the data preprocessing steps and their implementation in ArcGIS Pro, in order to show the air temperature dataset as 'Isosurface'. VA_3 only allows to apply UC_2—the visualisation of 3D air temperature values exceeding a certain value (e. g. 25°C). To implement the VA_3 tutorials and documentation provided in `ArcGIS Pro` were drawn to assistance and used as guideline [36, 33].

5.4.1 Data preprocessing

The datasets used to visualise VA_3 are the same which were used to visualise VA_2. Therefore the data preprocessing steps are not described at this section of the master thesis once again. Detailed information about the data preprocessing workflow can be found in Section 5.3.1.

5.4.2 Visualisation of VA_3 in ArcGIS Pro

Same as in VA_2, VA_3 can not be shared as 3D web scene, due to licence restrictions regarding the voxel layer. Therefore VA_3 was visualised in the 'Scene Window' of `ArcGIS Pro`. The visualisation workflow of VA_3 matches with the visualisation workflow of VA_2 (see: Figure 5.18) in four of the five work steps and therefore will not be described in this section again. The only difference is that in work step five not 'Sections' have to be created, but 'Isosurfaces'.

In the scope of this master thesis a scene showing a single isosurface visualising UC_2—the 3D air temperature exceeding 25°C—will be used to conduct the following HE of the VAs (see: Figure 5.23). The colour setting of the isosurface is set to red in the 'Voxel Exploration' window.

As further example, a local scene containing four different isosurfaces was created (see: Figure 5.24). The isosurface showing temperature values around 20°C, 21°C, 23°C and 24.5°C were coloured 'Lapis Lazuli', 'Sugilite Blue', 'Macaw Green' and 'Mars Red' in each 'Voxel Exploration' window.

5.5 RESULTS

This sections reports the results of the visualisation of VA_1, VA_2 and VA_3.

5.5.1 Point clouds (VA_1)

In VA_1 the preprocessed components of the 3D city model are integrated in CesiumIon and visualised as 3D Webscene in Cesium Stories. The 3D air temperature data is visualised as point cloud by using 2D billboards in a 3D reference space. The air temperature value of each billboard features a certain colour value. The billboard features of the point cloud have a horizontal distance of around 30 m and are aligned to the DTM in five layers. Orthophotos of the ROI are texturing the surface. The building models are coloured white.

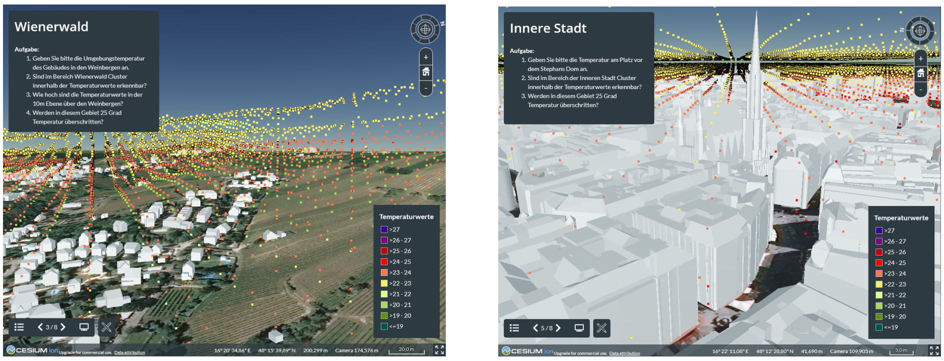


Abbildung 5.20: Visualisation of UC_1 of VA_1–Point Clouds

VA_1 enables the visualisation of UC_1—a continuous visualisation of the 3D air temperature data—and of UC_2—the visualisation of air temperature values exceeding a certain value (25°C) (see: Figure 5.20 and Figure 5.21). For the following evaluation procedure both UCs were generated within CesiumStories (see: Chapter 6).

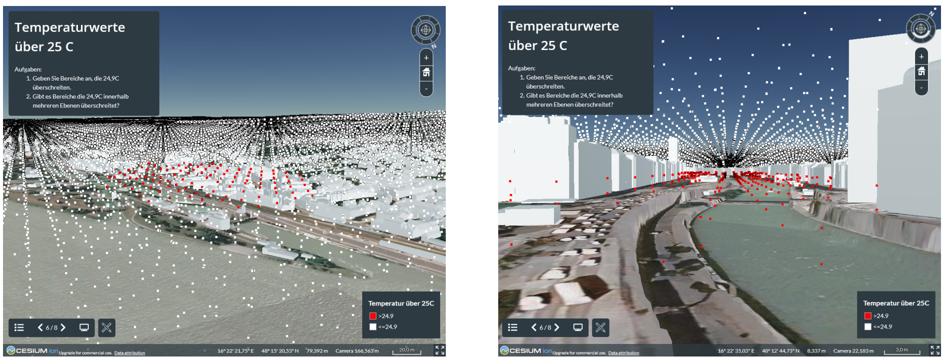
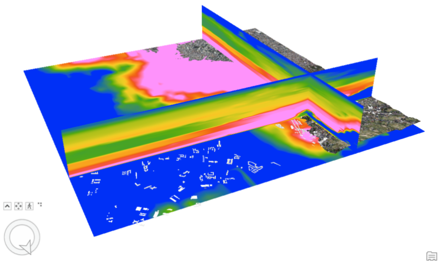


Abbildung 5.21: Visualisation of UC_2 of VA_1–Point Clouds

5.5.2 Cross section (VA2)

In VA2 the preprocessed components of the 3D city model are integrated and visualised in the 'Scene Window' of ArcGIS Pro. The 3D air temperature dataset is visualised on textured cross sections. Three sections, running from north to south, east to west and horizontally allow to query the 3D air temperature of the entire ROI (see: Figure 5.22). Same as in showcases using VA1, the surface is textured with orthophotos. The building models are coloured white.



(a)

(b)

Abbildung 5.22: 3D air temperature visualisation of (a) the entire ROI and (b) close up achieved with VA2–Cross Sections

VA2 allows to represent UC1, a continuous visualisation of the 3D air temperature data. Due to the characteristics of this VA it is not possible to create UC2, the visualisation of 3D air temperature values exceeding a certain value (e. g. 25°C).

5.5.3 Isosurface (VA3)

In VA3 the preprocessed components of the 3D city model are integrated and visualised in the 'Scene Window' of `ArcGIS Pro`. The 3D air temperature dataset is visualised as coloured isosurfaces. The surfcase is, similar as in the other showcases, textured with orthophotos. The building models are coloured white. For the further evaluation of this VA the showcase contains one isosurface (see: Figure 5.23).

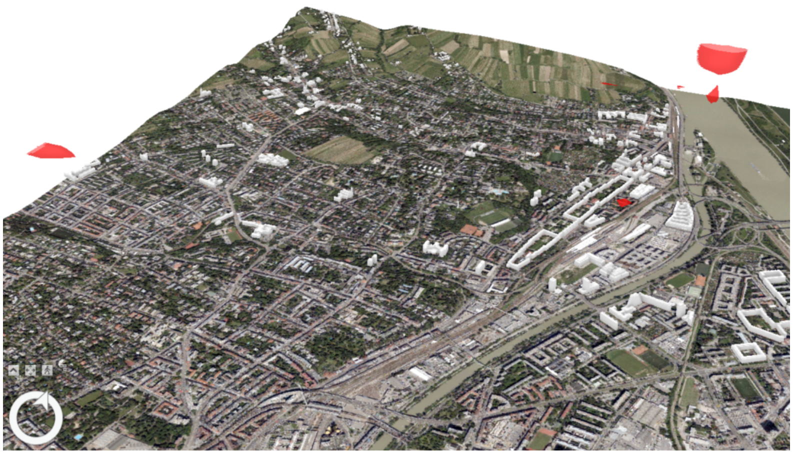


Abbildung 5.23: 3d air temperature visualisation of one defined value with VA2–Isosurface

VA3 allows to represent UC2, the visualisation of 3D air temperature values in a certain range. Due to the characteristics of this VA, it is not possible to create UC1, the continuous visualisation of the 3D air temperature data.

To show further possibilities of this VA the maximum of four isosurfaces are also represented in another showcase, which has not been evaluated by the experts (see: Figure 5.24).

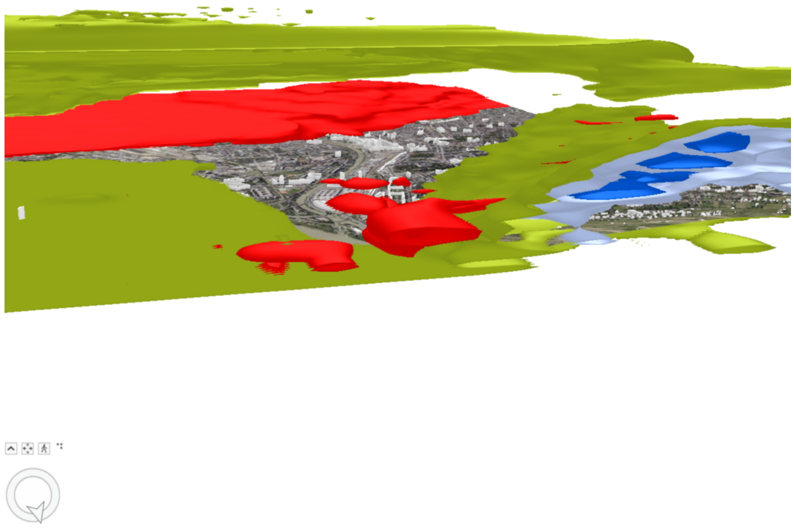


Abbildung 5.24: 3d air temperature visualisation a four defined values VA_3–Isosurface

6 EVALUATION OF THE VISUALISATION APPROACHES

Aim of this chapter is to describe the implementation of the evaluation of the visualisation approachs (VAs). Therefore in the following sections the used methods, the implementation of the evaluation method and the results of the evaluation process in detail. In the chapter, the identification, aggregation and definition of the severity of the usability problems (UPs) is elaborated as a basis to draw conclusions and to answer the research question in Chapter 7.

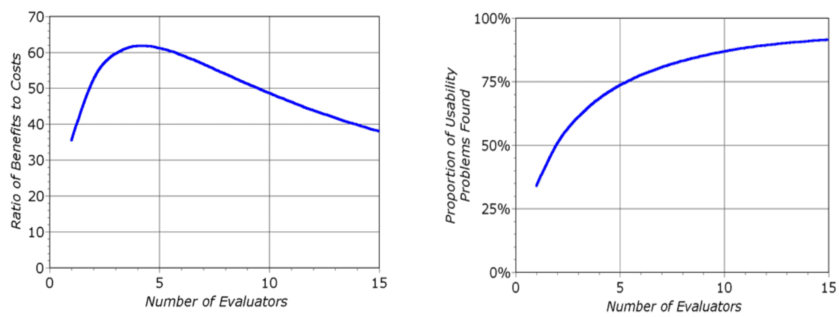
6.1 USED METHODS

For the evaluation of the differing visualisation approaches the Heuristic Evaluation (HE) method was chosen (see Section 2.5). The following Section 6.1.1 shows a brief insight about the characteristics of this method. Section 6.1.2 explains how the HE process was done technically.

6.1.1 Heuristic evaluation of geovisualisation

Heuristic Evaluation (HE) is an expert-based testing method proposed by Nielsen [93] and can be seen as formative assessment. Goal of a formative assessment is to provide ongoing feedback at an early stage of the development of an application [118]. HE was originally applied within the fields of Human-Computer Interaction (HCI). As further consequence this method entered the field of *information visualisation* and *geovisualisation*.

The aim of the evaluation method is to identify and to define the severity of the UPs. To carry out a HE, three to five experts with experience in data display or in usability should be consulted [129]. The reason for the small amount of experts is shown in Figure 6.1. The ratio of benefit and cost in relation to the number of evaluators shows the highest value between a number of three and five evaluators. Another important aspect is that five elevators are able to detect 75% of usability problems. Adding further elevators causes a saturation and does not lead to a linear or even a exponential growth of identified usability problems [94].



(a) (b)

Abbildung 6.1: Curves showing proportions of numbers of elevators in relation to (a) benefits and costs (b) found usability problems - [94].

Heuristic Evaluation basic procedure

Tory and Moller [129] structure the evaluation design of a HE in three steps (see Figure 6.2). The first step describes the *preparation* and contains the description of users and tasks, the determination of objectives and the selection of suitable heuristics and the selection of experts. The description of users and their user tasks is important, due to the fact, that selected usability experts might not be familiar with the target user and the users' needs. Selected heuristics will enable to test how well the tool meets the objectives and frame the evaluation process. As regards the selection of experts, it needs to be considered that they should have strong communication skills and experience conducting usability inspections and in the domain area [57, 129] (see Section 6.1.1). The first step of the HE procedure leads to a rapport which serves as a guideline for the expert sessions.

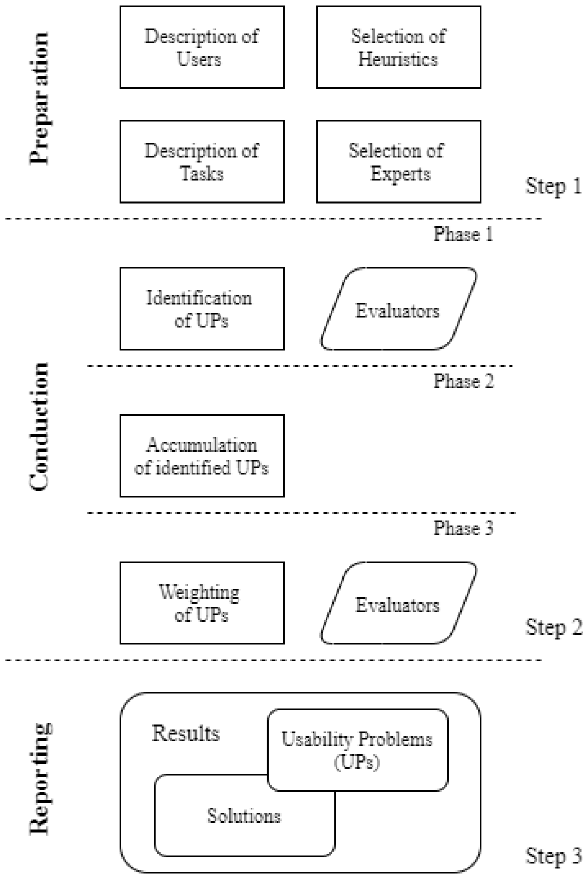


Abbildung 6.2: *HE flowchart* — based on Quiñones and Rusu [111], Tory and Moller [129].

The second step describes the *conduction* of the evaluation which can be, according to Quiñones and Rusu [111] separated into three phases. In the first phase usability problems have to be identified separately by experts based on heuristics or guidelines. It is important to focus on qualitative issues and to encourage evaluators to express their opinions in detail [129]. As a result of the first phase, identified problems have to be summed up in an individually list of usability problems. In the second phase the individual lists of usability problems have to be summarized in a unique list which will be presented to the evaluators in a second session. In the third phase each evaluator qualifies and scales the problems in terms of criticality, severity and frequency [111]. Quiñones and Rusu [111] therefore define the criticality scale as the sum of severity and frequency, severity scale as the degree of severity of identified usability issues and frequency scale as the degree of occurrence of the identified usability problem.

In the third step the results of the HE are *collected and summarized in a report*, which describes identified usability problems and may suggest solutions. In literature some HE integrate phase 3 into phase 1 to reduce time and effort of the evaluation process. For more detailed information Quiñones and Rusu [111] can be recommended.

Evaluators - a set of experts

Tory and Moller [129] recommend to choose usability experts with experience in conducting usability inspections, domain expertise and strong communication skills. Evaluators have to be independent of the development team. In literature evaluators with expertise in usability inspection and domain expertise are named *double specialists* [93] and recommended to favour over single or *regular* experts of usability [129, 111]. Nielsen [93] shows the proportion of usability found as a function of number of evaluators and their rate of specialisation (see Figure 6.3). Therefore the choice and availability of high qualified experts has a significant impact on the result of this evaluation method.

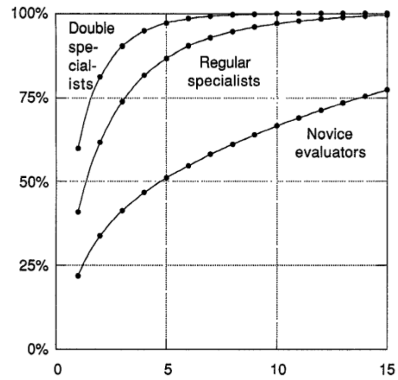


Abbildung 6.3: Proportion of usability problems found as a function of number of evaluators and their specialisation Nielsen [93].

Due to the scope of the master thesis the domain expertise focuses on 3D city modelling and 3D geovisualisation of air data. Therefore suitable experts have to have expertise in the field of 3D geovisualisation, 3D air data visualisation and 3D city models.

Heuristics

Heuristics form a guideline for evaluators to discover usability problems [129] and focus the evaluation on certain predefined areas [142].

As already stated abouve, HE was originally invented in the field of Human-Computer Interaction (HCI). Therefore several sets of heuristics are available (e. g. 10 usability heuristics developed by Nielsen [94]) and have been used by the HCI community. According to Williams et al. [142] in the field of data visualisation or information visualisation adopted heuristics are applied (e. g. usability heuristics for information visualisation developed by Forsell and Johansson [39] or by Väätäjä et al. [138]). At this point neither the geovisualisation community nor the 3D visualisation community has adopted a common set of heuristics. In the literature research heuristics dealing with 3D geovisualisation could not be identified.

In literature it is recommended to modify heuristics used in HCI and in other areas of data visualisation or to create own criteria based on user discussions [83]. Within the scope of this master thesis a mix of both approaches was applied. Existing heuristics were selected and modified and own criteria created based on own assumptions (see Section 6.2.1).

6.1.2 Remote Testing

Due to the COVID19 situation during the elaboration of these this thesis, the HE needed to be performed via a process of remote testing. In literature three different types of remote testing are mentioned: *remote moderated testing*, *automated remote testing* or mixture of both approaches [40, 88]. The users of automated remote testing or unmoderated remote testing were not supervised. The results were gained with low costs, but deliver low-quality findings comparing to remote moderated testing [89]. In the framework of this master thesis, remote moderated usability testing was chosen as the type best fitting to the situation, therefore this method is described in more detail.

In the setting of a remote moderated test the participant and moderator are connected in real time and take place online. Aim of this testing situation is to exchange impressions and expectations. The test orientates on a previously designed guideline. The results of this form of testing possess a qualitative character. This method allows to overcome spatial distances, other forms of restrictions and allow to observe the participant in his or her natural environment. It is technically possible by means of native or browser-based screen sharing tools [88]. According to Friedmann [40] following conditions should be fulfilled to guaranty a proper process: use of a simple screen sharing solution, no or little installation necessary, support of the operating system or browser and that no admin rights are necessary. Section 6.2.1 describes the applied meeting tools of this master thesis in detail.

6.2 IMPLEMENTATION OF THE HEURISTIC EVALUATION

The following section describes the implementation of step 1 and step 2 of the HE (see Figure 6.2). Section 6.2.1 lists the selected experts, the applied heuristics and defines users and their tasks. Section 6.2.2 describes the process of the identification, aggregation and scaling of UPs of varying visualisation approaches.

6.2.1 Preparation

This section describes the key elements of the HE implemented in this thesis. These elements were selected previous to the conduction of the evaluation and have been consulted with the supervisor.

Users and user tasks

The experts executing the HE have to slip into the role of the users. Therefore users have to be defined accurately. As described in Chapter 1 the visualisation of air temperature data in a 3D city model contributes to the public value of 3D data [54] and supports decision-making processes and monitoring [7]. On these grounds, *political decision-makers*, *urban planners* and *civil society* have been identified as potential user group of the selected VAs.

As regards user tasks, according to Shneiderman [117] and Keller and Keller [61] within big data visualisation, complex data sets in general and for performing a valid assessment of VAs it makes sense to search for relationships, clusters, gaps and outliers. Based on raised questions within the field of urban climate analyses as well as in big data visualisation following tasks have been identified and will be used during the HE: identification of *temperature value* at a certain point, *patterns or clusters* (e. g. UHI), *relationships* and *overstepping of defined temperature values* (e. g. 25°C) [61, 87, 117].

Used Heuristics

Throughout the literature review no set of heuristic dealing with usability problems for 3D geovisualisation was identified. Therefore the set of heuristics describing usability problems for information visualisation systems developed by Forsell and Johansson [39] was utilized and completed with own assumptions. The selected set of heuristics and questions referring to associated usability factors are shown in Table 6.1.

Heuristics or usability principle	Usability factors
(H1) Information coding	Are *symbols* appropriate for the data represented, regarding their form and size? Are selected *colours* able to represent data information? Do selected colours cause distortions of perception? Do selected *textures* cause distortions of perception (e.g. surface texture)? Is the *resolution* of the visualisation suitable for the given task (e.g. 3d air temperature data, building models, surface texture and the digital terrain model)?
(H2) Spatial perception and orientation	Is it possible for the user to identify the *height value* of an element? Can the user estimate *distances* between elements? Can the user orientate within the model?
(H3) Aesthetic and minimalist design	Is there any problems regarding the aesthetic of the data visualisation? Are there any unnecessary data elements represented? Is the data presented in a simple format? Is the lack of white space between colour representations causing problems?
(H4) Interactivity and intuitivity	Are there any problems occurring relating to the interaction? Is the visualisation approach and the handling intuitive
(H5) Other	Any further problem, which cannot be assigned to the usability principle H1—H4.

Tabelle 6.1: Applied heuristics or usability principles and associated usability factors inspired by Dowding and Merrill [26].

Selected experts

Requirements concerning the set of experts were described in detail in Section 6.1.1. The selected set of experts was discussed with and approved by the supervisor of this master thesis. To meet demands of a master thesis on the one hand and to provide robust results on the other hand three evaluators have been selected.

The first evaluation expert (E1) is appointed to the professorship of 'Geodatenvisualisierung' at the Beuth Hochschule für Technik Berlin. E1 provides expertise in the fields of geovisualisation, 3D computer graphics and geoinformation and can be characterised as double expert with expertice in usability inspection and 3D geovisualisation [55].

As second evaluation expert (E2) a senior lecturer of the Institute of Geography at the Ruhr-Univerität Bochum could be gained as participant. E2 provides expertise in the fields of geovisualisation, web-cartography and cognitive behaviour and can be characterised as double expert [28].

Third evaluation expert (E3) is a managing director business development at `Virtual City Systems`, a leading company in the field of 3D geodata infrastructure. E3 provides expertise in the field of management, visualisation and utilisation of 3D city models.

Applied remote moderated testing tools

Two expert interviews were done by using `Zoom`, a meeting tool which was provided by the University of Vienna. The tool was used under student licence terms to conduct the expert interviews (see Section 6.2.2). The third expert interview was conducted by `Microsoft Teams`, a meeting tool which was hosted from the expert side.

6.2.2 Conduction

This section describes the practical implementation of the HE. The section is separated into the three phases of the conduction: *expert interviews* (phase 1), *accumulation and listing of identified UPs* (phase 2) and *weighting of UPs* (phase 3).

Expert interview

Within the expert interviews all visualisation approachs (VAs) were analysed by the selected experts (see: Section 6.2.1). Aim of phase 1 of the the conduction of the HE was to identify potential usability problems. The planned duration of each interview was one hour.

The expert interview can be differentiated into following sections: *introduction*, *evaluation of the VAs* and *outlook and feedback*. An overview of the exact schedule and workflow is shown in Figure 6.4.

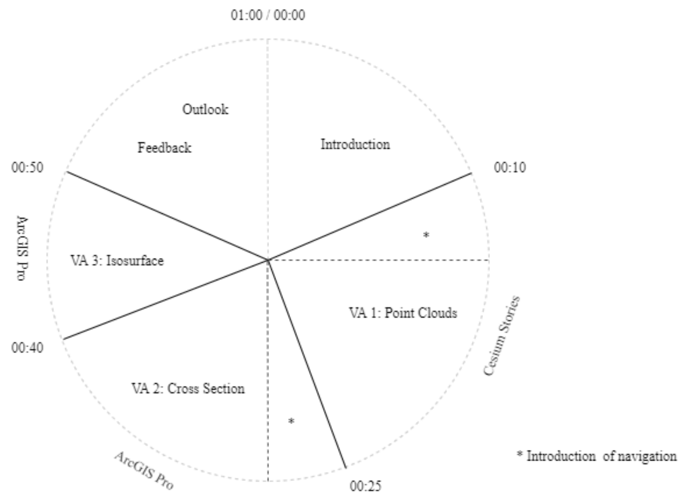


Abbildung 6.4: Schedule and workflow of the expert interview.

Section *introduction* contained a brief presentation of already implemented working steps and goals of the master thesis. The role of the expert interview within the thesis and how findings allow to answer the underlying research question were described. The procedure of the evaluation was explained and the chosen VAs demonstrated. The participant experts were asked to specify their experience in the fields of HE, 3D air data visualisation, 3D city model and 3D geovisualisation (see Table 6.2). Experts were requested to slip into the role of users to apply defined tasks as described in Section 6.2.1.

The *evaluation of the VAs* was done by remote moderated testing. All sessions have been recorded to ease the evaluation process. The given time for the evaluation of each VA was ten minutes. Five minutes were used to boot the visualisation tools and to introduce the navigation.

Expert	Heuristic Evaluation	3D air data visualisation	3D city model	3D geovisualisation
E_1	x			x
E_2	x	x	x	x
E_3		x	x	x

Tabelle 6.2: Experience of the evaluators in defined fields.

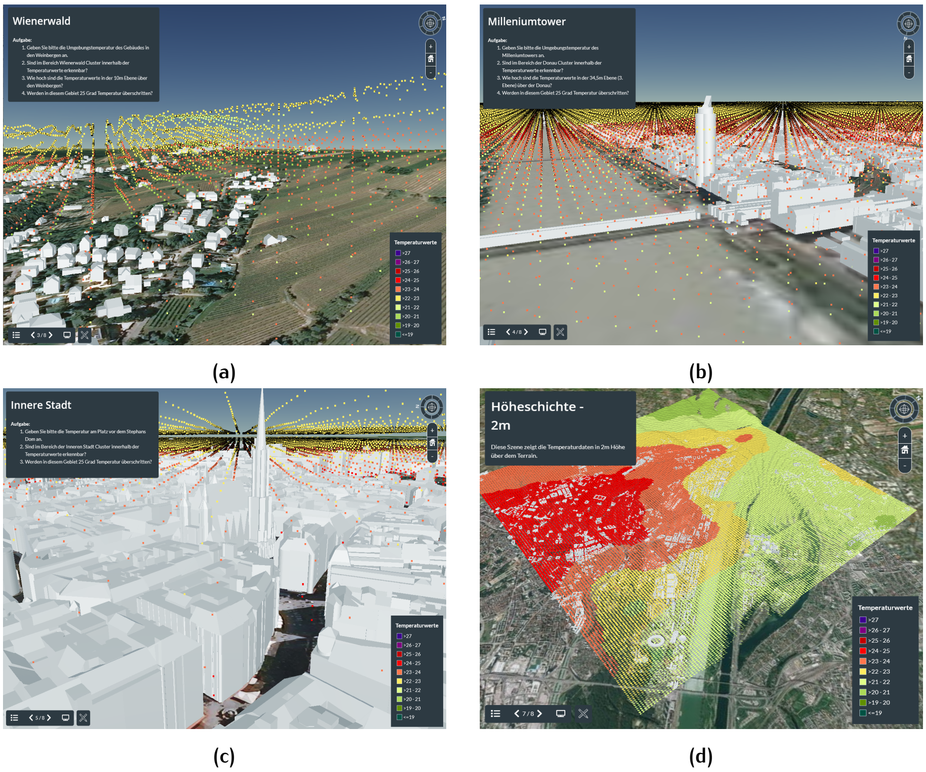


Abbildung 6.5: Exemples of set bookmarks in Cesium Stories: (a) Vienna Woods (b) Millenium Tower (c) Inner City (d) Layer at a height of two meters.

The first VA to evaluate was point clouds visualised in Cesium Stories. The second and third VA to evaluate was cross sections and isosurface visulised in ArcGIS Pro. In the first and third expert interview VA1 was shared as link, which allowed to host the visualisation on expert side. To moderate and document the evaluation process the experts shared their desktop. In the second expert interviews, VA1 was hosted by the moderator due to performance problems on the expert side. Therefore the desktop was shared and the navigation within the 3D city model was done by the moderator. In all expert interview VA2 and VA3 were hosted on moderator side. To conduct the evaluation in the first and third expert interview, remote control was given to the expert. In the second expert interview the desktop was shared and navigation within the 3D city model was done by the moderator.

To ease the navigation within Cesium Stories, bookmarks for points of interest were set (see Figure 6.5). Selected points of interest were: *Vienna Woods*, *Millenium Tower*, *Inner City*, *entire ROI* or *Layer at a height of two meters*. A different approach was applied for VA2 and VA3. Due to licence restrictions no bookmarks were set within ArcGIS Pro. A guideline facilitated the conduction of the expert interview.

The experts reflected the functionality of the VAs based on selected usability principles by questioning the related usability factors (see: Table 6.1).

Upon the recommendation of the first expert the following two evaluations contained specific tasks like:

- *Specify the ambient temperature of a defined location.*

- *What are the temperatures at a defined height?*
- *Can you identify areas which exceed a temperature value of* 25°C*?*
- *Are in a defined area clusters of same temperature values identifiable?*

After conducting all expert interviews the identified UPs were accumulated in the second phase of the evaluation process.

Following the evaluation of all three VAs, experts were informed about their further involvement in the evaluation process. An *outlook* for tasks to come was therefore given. Within the scope of the first two expert interviews a debriefing of the interview was held. Findings focus on the standardization of the evaluation process and the ascertainment of the given tasks. Parts of these remarks were integrated in the following expert interviews and the guideline was continuously adopted. Because of the particular characteristics of the HE, a guideline in progress can deliver a bigger range of identified UPs and must not be seen as negatively affecting the evaluation process.

Accumulation and listing of UPs

Aim of phase 2 of the conduction of the HE is to list and sum up identified usability problems (UPs) for each visualisation approach (VA). The gathered lists are needed to conduct the severity rating in phase3. The provided spreadsheets are aligned to Michael Djak [86].

As described in Figure 6.6, to create these lists recordings of the expert interviews were rewatched, mentioned usability problems were noted and assigned to heuristics. In a next step, matching usability problems found by different experts were merged. Based on this working steps a list of usability problems for each visualisation approach was produced.

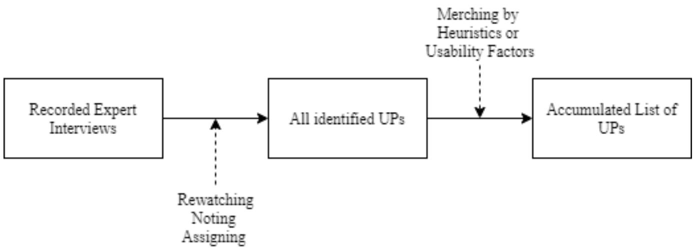


Abbildung 6.6: Schedule and workflow of the expert interview.

The VA_1 'Point Clouds' shows 19 identified UPs. The VA_2 'Cross Section' and VA_3 'Isosurface' show 5 or 4 identified UPs.

Beneath the notation of UPs, further comments of the expert regarding positive findings, ideas or personal opinions of the technical implementation were noted within this work step.

Severity Rating—Weighting of the UPs

In phase 3 of the HE the experts had to conduct a severity ranking of the identified and accumulated usability problems. Therefore a questionnaire was created. Within this questionnaire each previously identified usability problem was described, illustrated by a screenshot and equipped with a five-level Likert Scale (see: Figure 6.7). The design of the severity rating and the Likert items were designed in accordance with Michael Djak [86] and Nivala et al. [99].

The Likert items used in the evaluation process were:

0 — no usability problem

1 — cosmetic usability problem

2 — minor usability problem

3 — major usability problem

4 — catastrophic usability problem

Cosmetic UPs cause the feeling of unfinished design, but show a low priority to fix. Minor UPs are causing difficulties to use the application and show a moderate priority to fix. Major UPs makes the use of the application significantly difficult. There is a high priority to fix these kind of problems. Catastrophic UPs prevent the use of the application by users and must be fixed by all means.

To simplify and to speed up the evaluation process these sessions were not moderated. The experts were provided with the questionnaire and asked to fill it in on their own without assistance.

1.3 Wahrnehmungsschwierigkeiten der Temperaturwerte

Die Zunahme bzw. Abnahme der Temperaturwerte—in Abhängigkeit von deren Höhenlage—ist nicht oder nur schwer erkennbar.

Ort: Cesium Webscene - Bookmarks 2–5

Abbildung 3: Wahrnehmungsschwierigkeiten der Temperaturwerte

Severity Ranking 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐

Bitte hier Gewichtung vornehmen und zutreffende Kategorie ankreuzen.

Abbildung 6.7: Example of the severity rating of an identified UP.

In a further and concluding step the weighting of the UPs for each VA were summed up.

6.3 RESULTS

This section reports the results of the evaluation of the visualisation approaches VAs in detail. Identified usability problems (UPs) are listed and described, the weighting of UPs, are shown and further findings of the expert interview are stated.

6.3.1 Identified usability problems

This section lists and describes identified usability problems (UPs) of the three implemented visualisation approachs (VAs) *point cloud*, *cross section* and *isosurface*. Each UP identified in the expert review is assigned to one heuristic. As described earlier, the previously defined set consists of following heuristics: (H1) Information coding; (H2) Spatial perception and orientation; (H3) Aesthetic and minimalist design; (H4) Interactivity and intuitivity and (H5) Other.

Each UP is furthermore assigned to one or to both Use Cases (UCs). UC1 deals with the visualisation of continuous air temperature values. UC2 visualizes air temperature values exceeding a certain value (e. g. 25°C).

Table 6.3 lists 19 usability problems of VA1. 14 usability problems can be assigned to UC1, five to UC1 and UC2. Six usability problems are related to the heuristic (H1) Information coding, five UPs to (H2) Spatial perception and orientation, three UPs in each chase to H3 and H4 and two UPs to (H5) Other. 12 usability problems were identified by one expert. Six UPs were found by two experts and one UP by all three experts.

ID	Name	Heuristic	Use case	E_1	E_2	E_3
1.1	Air temperature visualisation is not shown at the beginning	H4	1	x		
1.2	Spatial patterns within air temperature data are not recognizable	H5	1	x		x
1.3	Perception difficulties of air temperature values	H2	1	x		
1.4	No possibility to interact with air temperature signatures	H4	1	x		x
1.5	Unnecessary possibility to interact with building models	H4	1	x		
1.6	Classes of air temperature data are difficult to distinguish by colour	H1	1	x	x	
1.7	Red-green colour blindness is not considered	H1	1		x	
1.8	High number of classes reduces information perception	H1	1		x	
1.9	Difficult to detect altitude of air temperature signatures	H2	1	x	x	
1.10	Distance between air temperature signatures on horizontal as well as vertical plane difficult to estimate	H2	1; 2	x		
1.11	Distance between air temperature signatures and other elements of the 3D city model difficult to estimate	H2	1	x	x	x
1.12	Loss of 3D information in total view	H2	1; 2	x		
1.13	Contrast decrease or increase of air temperature signatures depending on terrain texture	H1	1	x	x	
1.14	Distorted perception of air temperature signatures due to different backgrounds	H1	1		x	
1.15	Building models cannot be faded in and out	H3	1	x		
1.16	High performance demand due to rendering of all background elements	H3	1; 2	x		
1.17	Air temperature signatures are displayed too small at high zoom level	H1	1; 2			x
1.18	Air temperature signatures are hidden by other air temperature signatures	H3	1		x	x
1.19	Air temperature signatures are overlaid by buildings	H5	1; 2		x	

Tabelle 6.3: List of usability problems of VA1 (point cloud).

Table 6.4 lists 5 usability problems of VA2. Due to the characteristics of the visualisation approach all usability problems were assigned to UC1. Two usability problems are related to heuristic (H4) Interactivity and intuitivity and one usability problem to H1, H2 or H5. One usability problem was identified by a single expert. All other usability problems were mentioned by two experts.

ID	Name	Heuristic	Use case	E_1	E_2	E_3
2.1	Absence of a play function	H4	1	x		
2.2	Exact temperature values at cross sections not definable	H1	1	x	x	
2.3	Absence of a height scale	H2	1	x	x	
2.4	Difficult positioning of cross sections at requested position	H4	1	x		x
2.5	Cross sections are overlaying elements of the 3D city model	H5	1		x	x

Tabelle 6.4: List of usability problems of VA2 (cross section).

Table 6.5 lists 4 usability problems of VA3. Due to the characteristics of the visualisation approach all usability problems were assigned to UC2. Two usability problems are related to heuristic (H2) Spatial perception and orientation and one usability problem to H3 and H5. Two usability problems were identified by a single expert. One usability problem was mentioned by two experts and one usability problem by all three experts.

ID	Name	Heuristic	Use case	E_1	E_2	E_3
3.1	Perception difficulties of visualised surface	H3	2	x		
3.2	Unclear spatial spread of visualised surface	H2	2	x	x	x
3.3	Difficult to detect altitude of visualised surface	H2	2	x	x	
3.4	Loss of information	H5	2			x

Tabelle 6.5: List of usability problems of VA3 (isosurface).

6.3.2 Severity Rating of UPs

This sections shows the results of the severity rating of the usability problems of the three implemented visualisation approachs (VAs) *point cloud, cross section* and *isosurface*.

		Severity Rating			
ID	Name	E_1	E_2	E_3	∅
1.1	Air temperature visualisation is not shown at the beginning	1	4	0	1.67
1.2	Spatial patterns within air temperature data are not recognizable	4	3	3	3.33
1.3	Perception difficulties of air temperature values	4	3	2	3.00
1.4	No possibility to interact with air temperature signatures	3	2	1	2.00
1.5	Unnecessary possibility to interact with building models	2	1	0	1.00
1.6	Classes of air temperature data are difficult to distinguish by colour	1	1	1	1.00
1.7	Red-green colour blindness is not considered	3	1	0	1.33
1.8	High number of classes reduces information perception	2	3	1	2.00
1.9	Difficult to detect altitude of air temperature signatures	2	4	2	2.67
1.10	Distance between air temperature signatures on horizontal as well as vertical plane difficult to estimate	4	1	3	2.67
1.11	Distance between air temperature signatures and other elements of the 3D city model difficult to estimate	3	2	3	2.67
1.12	Loss of 3D information in total view	2	1	2	1.67
1.13	Contrast decrease or increase of air temperature signatures depending on terrain texture	1	3	1	1.67
1.14	Distorted perception of air temperature signatures due to different backgrounds	1	2	1	1.33
1.15	Building models cannot be faded in and out	1	1	0	0.67
1.16	High performance demand due to rendering of all background elements	2	2	1	1.67
1.17	Air temperature signatures are displayed too small at high zoom level	2	3	2	2.33
1.18	Air temperature signatures are hidden by other air temperature signatures	3	1	2	2.00
1.19	Air temperature signatures are overlaid by buildings	3	3	1	2.33
	Average severity ∅	2.32	2.16	1.37	1.95

Tabelle 6.6: Severity rating of usability problems regarding VA1 (point cloud).

Table 6.6 shows the severity ration of each expert and the average value of usability problems regarding VA1. UP1.2 *Spatial patterns within air temperature data are not recognizable* presents the highest average value of all UPs with 3.33. UP1.15 *Building models cannot be faded in and out* presents the lowest average value of all UPs with 0.67. All UPs were weighted on average with 1.95. Evaluator E_1 rated all UPs with the highest average value (2.32), evaluator E_3 with the lowest average value (1.95). Four UPs were classified by one expert as 'no usability problem'. 13 UPs were—at least by one expert—weighted as 'major usability problem' or worse. Five UPs were—at least by one expert—classified as 'catastrophic usability problem'.

Table 6.7 shows the severity ration of each expert and the average value of usability problems regarding VA2. UP2.2 *Exact temperature values at cross sections not definable*

ID	Name	Severity Rating E_1	E_2	E_3	∅
2.1	Absence of a play function	1	2	1	1.33
2.2	Exact temperature values at cross sections not definable	2	4	0	2.00
2.3	Absence of a height scale	2	3	1	2.00
2.4	Difficult positioning of cross sections at requested position	3	1	1	1.67
2.5	Cross sections are overlaying elements of the 3D city model	2	1	1	1.33
	Average severity ∅	2.00	2.20	0.80	1.67

Tabelle 6.7: Severity rating of usability problems regarding VA2 (cross section).

and UP2.3 *Absence of a height scale* present the highest average value of all UPs with 2.00. UP2.1 *Absence of a play function* and UP2.5 *Cross sections are overlaying elements of the 3D city model* present the lowest average value of all usability problems with 1.67. All UPs were weighted on average with 1.67. Evaluator E_2 rated all UPs with the highest average value (2.20), evaluator E_3 with the lowest average value (0.80). One UP was classified by one expert as 'no usability problem'. 3 UPs were—at least by one expert—weighted as 'major usability problem' or worse. One UPs was—at least by one expert—classified as 'catastrophic usability problem'. UPs regarding UC1 show a total average value of 2.13.

ID	Name	Severity Rating E_1	E_2	E_3	∅
3.1	Perception difficulties of visualised surface	3	3	1	2.33
3.2	Unclear spatial spread of visualised surface	2	3	2	2.33
3.3	Difficult to detect altitude of visualised surface	3	4	3	3.33
3.4	Loss of information	1	3	1	1.67
	Average severity ∅	2.25	3.25	1.75	2.42

Tabelle 6.8: Severity rating of usability problems regarding VA3 (isosurface).

Table 6.8 shows the severity ration of each expert and the average value of usability problems regarding VA3. UP3.3 *Difficult to detect altitude of visualised cluster* presents the highest average value of all UPs with 3.33. UP3.4 *Loss of information* shows the lowest average value of all usability problems with 1.67. All UPs were weighted on average with 2.42. Evaluator E_2 rated all UPs with the highest average value (3.25), evaluator E_3 with the lowest average value (1.75). All four UPs were—at least by one expert—weighted as 'major usability problem' or worse.

VA3 shows the highest total average severity rating with 2.42, VA2 shows the lowest total average severity rating with 1.67.

6.3.3 Further findings

The following section describes further findings regarding all three visualisation approachs and general notions. These findings were stated by the evaluators during the expert interview and transcribed in the second phase of the conduction of the heuristic evaluation (see: Section 6.2.2).

Point clouds (VA1)

Spatial pattern are hard to grasp in VA1. There is too much information visualised on screen. Therefore experts quote the huge amount of point signatures as problem. Experts suggest that the reduction of layers and the application of LODs would lead to a gain of informativity and increase performance.

Camera perspective affects information perception. It is therefore important to move through the scene. One or more experts assume that surface texture eases the orientation. At low zoom level and larger point signature the perception of the information is easier.

Cross Section (VA2)

The design of the control elements and interaction possibilities allow to focus on the visualised information. VA2 convinces because of its approachability. According to experts patterns within the visualised air temperature date are good to grasp.

Isosurface (VA3)

Instinctive interaction with the visualized area is not possible. Pop-up information about the visualized area is recommended. This VA only allows to deal with UC2. This circumstance lead to a loss of information.

General notions

Experts suggest to show all informations by default, with the option to hide unneeded information. Usability of all three VAs depends on the skills of the user to navigate within the scenes. Advantage or disadvantage of the VAs depends on the underlying data base and the requirements. Two of three evaluators label Cross sections (VA2) as their preferred application.

7 DISCUSSION AND CONCLUSION

7.1 RESEARCH QUESTION

The research question answered in this master thesis is: *How can 3-dimensional air temperature data be visualized within a 3D city model and how do implemented visualisation approachs (VAs) perform in terms of usability?* In the thesis, this research question has been split into two parts which were answered separately.

The first part of the research question deals with the question: *How can 3D air temperature data be visualized within a 3D city model?*

To answer this part of the research question, two subquestions were formulated and had to be answered first. Subquestion 1 asks: *What are potential 3D VAs to visualise 3D air temperature data?* This subquestion has been answered by a comprehensive analysis of literature, blogs and related showcases. As potential VAs, point cloud, cross section, isosurface, polygon meshes or 3D polygons were identified. Based on assumptions that the VA mesh and VA 3D polygon lead to occlusions and to a reduction of information recognition the visualisation approaches point cloud (VA_1), cross section (VA_2) and isosurface (VA_3) were selected for a further practically implemented.

The second subquestion asks: *What are the main work steps to visualise 3D air temperature data within a 3D city model?* To answer this subquestion, the practical implementation of the VAs into a 3D city model was conducted and necessary work steps were derived from the implementation procedure. The work steps to visualise 3D air temperature data within a 3D city model are in general (1) the *data preprocessing* and (2) the *visualisation* of the preprocessed 3D air temperature data within a visualisation application. Derived from the implementation process of VAs_1, VAs_2 and VAs_3 following preprocessing steps can be listed: (1.1) to interpolate the available 2D air temperature dataset to increase their spatial resolution, (1.2) to convert the raster dataset in point features, (1.3) to add surface information and the offset to the point features, (1.4) to transform the 2D point features into 3D point features and (1.5) to convert the dataset into a data format which can be processed by the visualisation application. The order of the preprocessing work steps can vary, depending from the applied VA. The data visualisation process within a visualisation application can be split into following work steps: (2.1) the integration of the preprocessed dataset, (2.2) the selection of the VA, (2.3) the definition of visualisation parameters (e. g. colour of the temperature value) and (2.4) the delivery as web scene or an equivalent format.

Based on the answers of subquestion 1 and subquestion 2, the first part of the research question—*How can 3D air temperature data be visualised within a 3D city model?*—can be answered. 3D air temperature data can be visualized within a 3D city model using the VAs point clouds (VA_1), cross sections (VA_2) or isosurfaces (VA_3). This statement bases on the practical implementation of all three VA in the scope of this master thesis. The three implemented VAs based on 3D air temperature data provided by a regional climate model and were intersected with parts of the 3D city model of Vienna using the applications Cesium stories and ArcGIS Pro.

VA_1 provides a dense point cloud of coloured 2D billboards in a 3D reference space of the 3D air temperature dataset. The distance between the visualised point elements measures 50 m. The visualisation of all available point elements of the ROI at the same time is possible, but causes several usability problems, i. e. symbol occlusion or wrong viewer's appreciation of the depth relations between object in a scene.

VA_2 shows three coloured cross sections visualising the 3D air temperature dataset. The sections runs from north to south, east to west and horizontally. The VA allows to view the air temperature values at each point of the ROI. Comparing to VA_1, VA_2 can be considered as further developed, due to the fact that several methods to solve known UP, occurring in 3D visualisation, have already been reconsidered (e. g. data minimization). This VA primarily allows to apply UC_1, the continuous visualisation of the air temperature data.

VA_3 uses isosurfaces to visualise the 3D air temperature dataset. The isosurface shows a surface representing a defined value within the volume of the 3D air temperature dataset. In the scope of the master thesis the visualised air temperature value is set to 25°C. Limitation of this VA is, that it only allows to apply UC_2, the visualisation of a certain temperature value. The advantages of this VA become more visible, focusing on other tasks (e. g. showing UHI or the violation of threshold values).

To answer the second part of the research question, two further subquestions were formulated. Subquestion 3 asks: *Which evaluation method is suitable to evaluate the usability of the applied VAs?* Also this subquestion was answered by implementing a comprehensive literature research process. Literature research revealed that several evaluation methods in the categories expert-based testing, automated testing and user-based testing are applicable to evaluate VAs (e. g. cognitive walkthrough, field tests). Due to the early stage of the developed VAs and the time requirements of usability tests, a Heuristic Evaluation (HE)—an expert-based testing method—was chosen. The goal of a HE is to identify and rank usability problems (UPs) within an application. This method allows to evaluate VAs at an early stage of the development process and even small amount of experts (n=3) delivers robust results. Nevertheless, the reliability of the results depends heavily on the expertise of the evaluators. To conduct the HE experts in the fields 3D geovisualisation, web-cartography, 3D geodata infrastructure and usability inspection could be recruited. The expert interview of the HE was held online under the use of meeting tools and delivered lists of identified UPs for each VA. This evaluation method allowed to draw conclusions about the usability of the chosen VAs.

Subquestion 4 asks: *Which set of heuristics is appropriate to conduct a heuristic evaluation of the applied VAs?* Heuristics, also known as usability principles, form a guideline for evaluators to discover UPs and focus on potential problem areas. In the field of Human-Computer Interaction (HCI) and data visualisation, sets of heuristics were already established (e. g. Nielsen's 10 usability heuristics [94]). But in the field of 3D geovisualsiation no established set of heuristics has been found during literature research. To solve this lack of a suitable set, heuristics used in HCI were modified or created based on own assumptions what potential problem areas could be. The set of heuristics used within the scope of the work are therefore: *information coding*, *spatial perception and orientation*, *aesthetic and minimalist design*, *interactivity and intuitivity* and *other*. The results of the HE showed, that around 82% of the identified UPs can be aggregated to the first four heuristics. Around 18% of the identified UPs can be aggregated to the category 'Other'. This result led to the assumption that the applied set of heuristics is appropriate to conduct a heuristic evaluation, but as recommanded in Section 7.3 further research has to be done to validate it.

Answering subquestion 3 and 4 allows to deal with the second part of the research question: *How do selected VAs perform in terms of usability?* As expected the implemented VA show different results regarding their performance in terms of usability. Focusing on the amount of identified UPs and their severity rating delivers following results:

VA_1 shows 19 usability problems with an average severity rating of 1.95. 13 of these identified UPs are classified as major UP or catastrophic UP by at least one expert. The UP 1.2 ‘Spatial patterns within air temperature data are not recognizable’ shows the highest severity rating and is categorized by all experts as major or catastrophic UP. Four of five UPs with the highest severity rating can be assigned to the usability principles ‘Spatial perception and orientation (H2)’. The usability of VA_1 was—beneath other usability problems—limited because of their huge amount of point signatures.

UPs with the highest severity rating can be assigned to the symbol occlusion and to the depth relations between objects in a scene. These findings are consistent with previously conducted research. In literature these problems are well documented and described as *symbol occlusion within 3D scenes* [116] or *viewer's appreciation of the depth relations between objects in a scene* [140]. Shepherd [116] lists several solutions for the problem (e. g. object culling, object minimization, object displacement, symbol transparency). These occlusion problems can also be minimized by an interactively moving of the viewpoint, which could be confirmed based on conducted observations within the evaluation process.

Nevertheless, the VA_1 can be characterised as the most incomplete VA, based on the number of identified UPs.

VA_2 shows five usability problems with an average severity rating of 1.67. Three of these identified UPs are classified as major or catastrophic UP by at least one expert. The UPs 2.2 ‘Exact temperature values at cross sections not definable’ and ‘2.3 Absence of a height scale’ were rated with the highest severity rating. If you compare these problems with the UP 1.2 of VA_1, where all experts rated the problem major or catastrophic, you can see that only one expert rated UP 2.2 and UP 2.3 as major or catastrophic UP and one expert characterised them as no or as cosmetic UP. This difference in rating may be due to a misleading formulation of the UP or due to differences in the expert background. Two UPs can be assigned to the heuristic ‘Interactivity and intuitivity’. Due to licence restrictions the VA_2 was shown in ArcGIS Pro via remote desktop and not as web-scene. This circumstance impacts the result of the HE, because it can be assumed that the interactivity within the web-scene causes fewer problems. This leads to the assumption that this VA, represented as web-scene, would lead to an even lower severity rating. To sum up the results, this VA shows the lowest severity rating and can therefore be identified as the most complete and suitable approach to visualise 3D air temperature data within a 3D city model. But nevertheless, the usability of this approach was—beneath other usability problems—limited because of their difficulty to positioning the section at a requested position.

VA_3 shows four usability problems with an average severity rating of 2.42. All four identified UPs are classified as major or catastrophic UP by at least one expert. UP ‘3.3 Difficult to detect altitude of visualised surface’ shows the highest severity rating and is categorized by all experts as major or catastrophic UP. Two of four VAs with the highest severity rating can be assigned to the usability principles ‘Spatial perception and orientation (H2)’. The usability of this approach was—beneath other usability problems—limited because of the difficulty to detect the altitude of the visualised surface. Due to the assumption that VA_3 is already at a later stage of the software development cycle and the fact, that major or catastrophic UP are known problems in 3D geovisualisation, it can be assumed the accruing UPs can not be solved.

As stated before it is important to mention that differences between VA_1 on the one hand and VA_2 and VA_3 on the other hand can be explained due to the genesis of the VAs. VA_1 is the early stage of the software development cycle work, whilst VA_2 and VA_3 are visualisation approaches at a later stage of the software development cycle provided by a leading GIS software developer.

During the expert interviews the evaluators also stated their opinion on the individual VAs. In the scope of the evaluation process two of three evaluators label VA_2 ‘Cross Section’ as their preferred VA to visualise 3D air temperature date in a 3D city model and conduct given tasks.

The results of the severity rating and further findings lead to the conclusion, that VA2 is the preferable solution to visualise 3D air temperature data and that to much 3D air temperature data visualisation leads to a reduction of information recognition.

The results of the HE and the comments of the experts also shows that the chosen VAs have reached the limits of 3D data visualisation as an exploratory and interpretative tool. This assumption corresponds with findings in previous work [116]. As Shepherd [116] stated:

> 'Rather than overload the z-axis, it might be more effective for the analyst to resort to map overly analyses or, [...] to adopt some form of dimension reduction techniques in order to simplify the data before or during the visualisation process.'

It therefore can be proposed to develop VA1 further, by implementing overly analyses or by adopting dimension reduction techniques, or to chose VA2 for the practical enrichment of the 3D city model of Vienna with 3D air temperature data. VA3 can be dropped.

The experts stated also further proposals. I. e. a combination of VA1 and VA2, depending on the zoom level. The VA 'Cross Section' can be applied by a low zoom level, point clouds by a high zoom level. Other proposals made by the experts were, that interaction with buildings should lead to a pop-up menu showing air temperature values of the surrounding, to enrich the GML data set with air temperature information, mulit-perspective views or to couple the data set with virtual or augment reality methods.

7.2 LIMITATIONS

During the implementation of the methodological approach, several limitations became obvious. Some of these limitations concern the data base: First, the components of the 3D city model were generated at different times. The creation time of building model, terrain and surface texture orientate on the update cycle of the 'Mehrzweckkarte'. Therefore the building model bases on orthophotos dated 2013. The DTM is dated 2017 and prior. The surface texture used in Cesium Stories is dated 2021, in ArcGIS Pro 2017 and prior. The data bases of the 3D air temperature data is dated 30.07.2016 at 00:00. This heterogeneity of the data base causes an inaccuracy of the data model.

Second, the visualized 3D air temperature data bases on a regional climate model with a spatial resolution of $1x1km$. By using interpolation methods, the resolution of the 3D air temperature data set was raised in VA1 to around $50x30m$, in VA2 and VA2 to a value above. But the manipulation of the initial 3D air temperature data sets leads to an increase of the variability of the finally implemented 3D air temperature data set.

Another limitation concerns the selection of the visualisation approaches: The three implemented VAs were selected based on literature research. Other promising VAs like 3D polygons or polygon meshes (see Chapter 3) were spared due to reduce the scope of the master thesis. It could be possible that one of this dropped approaches delivers less usability problems than the current ones. Especially the VA polygon mesh has been highlighted several times by experts during the evaluation process.

Also, the visualisation of the VAs was accomplished with CesiumIon and ArcGIS Pro. The selection of these to software solutions was based on literature research and their ability to visualise the selected VAs. It could be possible that other visualisation applications would deliver different results regarding usability and the severity of the UPs.

Some limitations address the evaluation process. First, in literature there is no set of heuristics yet defined for 3D air temperature visualisation or even 3D geovisualisation. The applied set of heuristics—which were chosen by own assumptions—allowed to perform the evaluation process, but further research in this field is necessary to further develop heuristics and support that the heuristic chosen are suitable.

Second, in the evaluation process itself three experts evaluated the different VAs who can be classified as double or regular specialist. According to literature this amount of participating experts manage to identify between 75% and 90% of all usability problems [93]. This means that 10 to 25% of existing usability problems were not found within the evaluation process. If two more experts could have been involved, between 85% and 97.5% of all usability problems could potentially have be identified.

Despite these limitation the master thesis provides an appropriate and structured overview on three approaches of visualising 3D air temperature in a 3D city model. The thesis details on a data transformation process beginning with a binary data format (netCDF) of a climate model and ending with a LiDAR point cloud data format (.laz) visualised in a web scene. The master thesis documents the necessary work steps of the implementation of the three most promising VAs in an existing 3D city model. The findings of the evaluation process and the comments of experts in the field of 3D geovisualisation and 3D city models provide a solid groundwork for further development of 3D air data visualisation and the enrichment of 3D city models.

7.3 FURTHER RESEARCH

The results and also the limitations of this master thesis reveal some research gaps and interesting research topics, where further work could be recommendable. The Heuristic Evaluation (HE) is an evaluation method applied at an early stage of the development of an application or approach. Normally, findings of the evaluation process and comments of the experts have to be implemented and VAs have to be further developed. For the cases of this thesis, the evaluation process revealed that i. e. the VA_1 point cloud should be intersected with the VA_2 cross section as suggested by experts. Another suggestion was to implement LODs to VA_1 point cloud and evaluate their usability. These modified VAs would then have to be further evaluated by using summative assessments like *usability tests* or *field tests*. These should be done due to the circumstance that usability inspection methods find problems which are overlooked by user testing and vice versa. Nielsen [95] therefore recommend the combining of several methods. After narrowing down the VAs to one approach and the description of the prototype, a *software inspection* should be conducted to debug and improve the code [95].

Further research can also focus on other domains like data base, data processing, data visualisation and evaluation. Due to permanent progress in upscaling of the climate models, the research design can be re-performed with data sets featuring a higher resolution. As an example for an extension of micro scale models to a size of entire urban areas, the German research project 'Urban Climate Under Change - $[UC]^2$' can be mentioned [48, 81, 114, 115]. It is worth to consider these advanced urban climate models as data base for further VAs as well as other air data sets (e. g. 'Lärminfokarte' of Austria) [15]. It can be recommended to integrated discrete data sources (e. g. measuring points) in the 3D city model. Also it can be useful to substitute the surface texture with Web Map Tile Service (WMTS) capable basic maps of the ROI. All data preprocessing steps can be automated. This allows to upscale represented points in time and to expand the related area.

The visualised building model bases on a version 2.0 citygml data set. As experts suggest, these data sets should be enriched with air temperature information. Findings of the implementation can also be integrated in the forthcoming version. In

CityGML 3.0 a revision of the concept of LOD will be implemented and more data storage methodologies beneath the OGC standard Geography Markup Language (GML) are considered N.N. [100], Kutzner et al. [66]. According to Ledoux et al. [69] the upcoming JSON-based encoding, CityJSON can be considered as a potential standard for exchanging 3D city models.

Biljecki et al. [9] identifies 44 Application Domain Extensions (ADEs), but none of them are dealing with air data. To empower the 3D city models and the CityGML data model it can be recommended to create an ADE focusing on the air data.

It should also be considered that there is an ongoing shift from authoritative data sources (e. g. the applied building model provided by the MA41) to asserted data sources (citizens as sensor) [45].

Based on finding in the literature research, the combination of physically measured data with qualitative and social values can be recommended. Billger et al. [14] points out that the developing of integrated planning models and the combination of physically measured data with qualitative and social values is of importance. For further work and to follow this recommendation, the combination of a city climate model with qualitative, social values (e. g. twitter data) can be suggested.

To increase the resolution of the 3D air temperature data set, the data set based on the regional climate model was interpolated. In further work it could be worth to analyse, which interpolation method is best suited to interpolate 3D air data within the Urban Canopy Layer (UCL).

In this thesis 3D air temperature is visualised statically. In further research 3D air temperature data should be visualised dynamically and it should be evaluated if dynamic 3D air temperature data visualisation delivers the same usability problems as static 3D air temperature data visualisation.

As already stated within limitations, the implementation of other VAs like 3D polygons or polygon meshes (see Chapter 3) can be recommended. It can be assumed that further VAs deliver new insights.

To solve known problems in 3D visualisation (e. g. symbol occlusion or viewer's appreaciation of the depth relations), several solutions were described in literature [116]. The use of dimension reduction techniques like object culling, object minimization or object displacement and the application of map overly analyses on the VAs can be studied in further research.

Last but not least, as currently there is a lack of sets of heuristics for 3D geovisualisation or 3D air data, some further work should be devoted to the development of suited visualisation heuristics. The methodological approach how to develop these sets is described by Quiñones et al. [112]. It is also worth to conduct or repeat user analyses and to identify user goals by using interviews and surveys [118].

LITERATURVERZEICHNIS

[1] Agugiaro, G. (2016). First steps towards an integrated CityGML-based 3D model of Vienna. In *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Science*, volume III-4, pages 139–146.

[2] AIT (2020). Digital Reslient Cities - Projects. www.ait.ac.at/digital-resilient-cities/projects. Accessed: 08-06-2020.

[3] Akenine-Möller, T., Haines, E., and Hoffman, N. (2018). *Real-time Rendering*. Taylor & Francis Ltd.

[4] Arnfield, A. J. (2003). Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island. *International Journal of Climatology*, 23(1):1–26.

[5] Bastin, J.-F., Clark, E., Elliott, T., Hart, S., van den Hoogen, J., Hordijk, I., Ma, H., Majumder, S., Manoli, G., Maschler, J., Mo, L., Routh, D., Yu, K., Zohner, C. M., and Crowther, T. W. (2019). Understanding climate change from a global analysis of city analogues. *PLOS ONE*, 14(7):1–13.

[6] Batty, M. (2012). Smart Cities, Big Data. *Environment and Planning B: Planning and Design*, 39(2):191–193.

[7] Batty, M., Chapman, D., Evans, S., Haklay, M., Kueppers, S., Shiode, N., Smith, A., and Torrens, P. M. (2000). Visualizing the city: communicating urban design to planners and decision-makers. *CASA Working Paper Series*.

[8] Bertin, J. (2010). *Semiology of Graphics: Diagrams, Networks, Maps*. ESRI PR.

[9] Biljecki, F., Kumar, K., and Nagel, C. (2018). CityGML Application Domain Extension (ADE): overview of developments. *Open Geospatial Data, Software and Standards*, 3(1).

[10] Biljecki, F., Ledoux, H., and Stoter, J. (2016). An improved LOD specification for 3D building models. *Computers, Environment and Urban Systems*, 59:25–37.

[11] Biljecki, F., Ledoux, H., Stoter, J., and Zhao, J. (2014). Formalisation of the level of detail in 3d city modelling. *Computers, Environment and Urban Systems*, 48:1–15.

[12] Biljecki, F., Stoter, J., Ledoux, H., Zlatanova, S., and Çöltekin, A. (2015). Applications of 3d city models: State of the art review. *ISPRS International Journal of Geo-Information*, 4(4):2842–2889.

[13] Bill, R. (2016). *Grundlagen der Geo-Informationssysteme*. Wichmann, Berlin Offenbach, 6., völlig neu bearbeitete und erweiterte auflage. edition.

[14] Billger, M., Thuvander, L., and Stahre Wästberg, B. (2016). In search of visualization challenges: The development and implementation of visualization tools for supporting dialogue in urban planning processes. *Environment and Planning B: Planning and Design*, 44.

[15] BMK (2020). Lärminfo.at. Lärminfo.at. Accessed: 12-02-2020.

[16] Bundesamt für Landestopografie - swisstopo (2019). 3D-Viewer - Die Schweiz in 3D. swisstopo.admin.ch. Accessed: 19-11-2019.

[17] Calvillo, N. (2008). In the Air. intheair.es.

[18] Calvillo, N. (2012). The affective mesh: air components 3D visualizations as a research and communication tool. In *Parsons Journal for Information Mapping*, volume 6.

[19] Cesium GS, Inc. (2019). Why cesium? cesium.com. Accessed: 10-12-2019.

[20] Cesium GS, Inc. (2020). Cesium sandcastle. cesium/sandcastle.com. Accessed: 14-05-2020.

[21] Chen, T., Rahman, A., and Zlatanova, S. (2008). 3d spatial operations for geo-dbms: geometry vs. topology. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 37.

[22] Chow, S. (2015). Analyze Four-Dimensional Observational Data with GridViz. https://cesium.com/blog/2015/08/27/gridviz/. Accessed: 30-06-2020.

[23] Christensson, P. (2020). The Tech Terms Dictionary - Wireframe Definition. www.techterms.com/definition/wireframe. Accessed: 17-06-2020.

[24] Cockburn, A. and McKenzie, B. (2002). Evaluating the effectiveness of spatial memory in 2D and 3D physical and virtual environments. In *Proceedings of the SIGCHI conference on Human factors in computing systems Changing our world, changing ourselves - CHI*. ACM Press.

[25] Damyanovic, D. (2019). Green and Reslilient City. www.green-and-resilient-city. Accessed: 02-01-2020.

[26] Dowding, D. and Merrill, J. (2018). The development of heuristics for evaluation of dashboard visualizations. *Applied Clinical Informatics*, 09(03):511–518.

[27] Dübel, S., Rohlig, M., Schumann, H., and Trapp, M. (2014). 2D and 3D presentation of spatial data: A systematic review. In *2014 IEEE VIS International Workshop on 3DVis (3DVis)*. IEEE.

[28] Edler, D. (2021). Dennis edler. https://www.researchgate.net/profile/Dennis-Edler. Accessed: 18-03-2021.

[29] Environmental Systems Research Institute, Inc. (Esri) (2018). 3D Visuzalization & Analytics - Get started with 3D mapping. . Accessed: 06-07-2020.

[30] Environmental Systems Research Institute, Inc. (Esri) (2020). i3s-spec. https://github.com/Esri/i3s-spec. Accessed: 24-06-2020.

[31] Environmental Systems Research Institute, Inc. (Esri) (2021a). 3D Polygon Feature. https://desktop.arcgis.com/de/arcmap/10.3/guide-books/extensions/3d-analyst/3d-polygon-features.htm. Accessed: 07-07-2021.

[32] Environmental Systems Research Institute, Inc. (Esri) (2021b). An overview of the Interpolation toolset. https://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analyst-toolbox/an-overview-of-the-interpolation-tools.htm. Accessed: 14-06-2021.

[33] Environmental Systems Research Institute, Inc. (Esri) (2021c). Create a voxel layer isosurface. https://pro.arcgis.com/en/pro-app/latest/help/mapping/layer-properties/voxel-layer-isosurface. Accessed: 22-06-2021.

[34] Environmental Systems Research Institute, Inc. (Esri) (2021d). Geostatistical layers in 3D. https://pro.arcgis.com/de/pro-app/latest/help/analysis/geostatistical-analyst/geostatistical-layers-in-3d. Accessed: 21-06-2021.

[35] Environmental Systems Research Institute, Inc. (Esri) (2021e). Voxel layer sections. https://pro.arcgis.com/en/pro-app/latest/help/mapping/layer-properties/voxel-layer-sections.htm. Accessed: 06-07-2021.

[36] Environmental Systems Research Institute, Inc. (Esri) (2021f). What is a voxel layer? https://pro.arcgis.com/en/pro-app/latest/help/mapping/layer-properties/what-is-a-voxel-layer. Accessed: 17-06-2021.

[37] Environmental Systems Research Institute, Inc. (Esri) (2021g). What is Empirical Bayesian Kriging 3D? https://pro.arcgis.com/de/pro-app/latest/help/analysis/geostatistical-analyst/what-is-empirical-bayesian-kriging-3d-.htm. Accessed: 18-06-2021.

[38] European Union (2020). INSPIRE knowledge base - Infrastructure for spatial information in Europe. inspire.ec.europa.eu. Accessed: 01-06-2020.

[39] Forsell, C. and Johansson, J. (2010). An heuristic set for evaluation in information visualization. In *Proceedings of the International Conference on Advanced Visual Interfaces - AVI '10*. ACM Press.

[40] Friedmann, T. (2018). Remote testing. www.blog.mediaworx.com/remote-testing. Accessed: 28-01-2021.

[41] Gabathuler, E., Eckert, S., Ehrensperger, A., and Bachmann, F. (2012). *Mapping and Geoprocessing Tools in Support of Rural Advisory Systems*.

[42] Gartner, G. (2012). Web Mapping 2.0. *Mitteilungen der Österreichischen Geographischen Gesellschaft*, 151:277–290.

[43] Giatili, S. G. and Stamatakos, G. S. (2012). A detailed numerical treatment of the boundary conditions imposed by the skull on a diffusion reaction model of glioma tumor growth. *Applied Mathematics and Computation*, 218(17):8779–8799.

[44] Givant, S. R. and Halmos, P. R. (2008). *Introduction to Boolean Algebras*. Springer-Verlag New York Inc.

[45] Goodchild, M. F. (2007). Citizens as sensors: the world of volunteered geography. *GeoJournal*, 69(4):211–221.

[46] Goodchild, M. F. (2008). Assertion and authority: The science of user-generated geographic content. www.geog.ucsb.edu/papers. Accessed: 24-02-2020.

[47] Goodchild, M. F. (2010). Twenty years of progress: GIScience in 2010. *Journal of Spatial Information Science*, (1).

[48] Halbig, G., Steuri, B., Büter, B., Heese, I., Schultze, J., Stecking, M., Stratbücker, S., Willen, L., and Winkler, M. (2019). User requirements and case studies to evaluate the practicability and usability of the urban climate model palm-4u. *Meteorologische Zeitschrift*, 28(2):139–146.

[49] Hartshorne, R. (2010). *Geometry: Euclid and Beyond*. Springer New York.

[50] Harvey, F. and Leung, Y. (2015). *Advances in Spatial Data Handling and Analysis: Select Papers from the 16th IGU Spatial Data Handling Symposium*. Advances in Geographic Information Science. Springer-Verlag GmbH.

[51] Hegarty, M., Smallman, H. S., Stull, A. T., and Canham, M. S. (2009). Naïve cartography: How intuitions about display configuration can hurt performance. *Cartographica: The International Journal for Geographic Information and Geovisualization*, 44(3):171–186.

[52] Held, G., Rahman, A., and Zlatanova, S. (2004). Web 3D GIS for Urban Environments.

[53] Höfler, A., Andre, K., Orlik, A., Stangl, M., Spitzer, H., Ressl, H., Hiebl, J., and Hofstätter, M. (2020). Klimarückblick Wien 2019. www.ccca.ac.at/KlimarueckblickWien2019. Accessed: 26-05-2020.

[54] Ho, S., Crompvoets, J., and Stoter, J. (2018). 3D geo-information innovation in Europe's public mapping agencies: a public value perspective. *Land*, 7(2):61.

[55] Hruby, F. (2021). Florian hruby. www.researchgate.net/profile/Florian-Hruby. Accessed: 18-03-2021.

[56] Huisman, O. and de By, R. A. (2009). *Principles of geographic information systems : an introductory textbook*. ITC Educational Textbook Series. International Institute for Geo-Information Science and Earth Observation, Netherlands.

[57] Interaction Design Foundation (2020). How to design an information visualization. www.interaction-design.org/how-to-design-an-information-visualization. Accessed: 05-02-2021.

[58] IPCC (2018). *Global Warming of* 1.5°C. *- An IPCC Special Report on the impacts of global warming of* 1.5°C *above pre-industrial levels and related global greenhouse gas emission pathwasys, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.*, chapter Summary for Policymakers, page 32. World Meteorological Organisation, Geneva, Switzerland.

[59] ISO/TC 211 (2003). ISO 19107:2003(en) Geographic information - Spatial schema. ISO 19107:2003(en). Accessed: 06-02-2020.

[60] José, R. S., Pérez, J., and González, R. (2012). Advances in 3D visualization of air quality data. In Leduc, T., Moreau, G., and Billen, R., editors, *Usage, Usability, and Utility of 3D City Models – European COST Action TU0801*. EDP Sciences.

[61] Keller, P. R. and Keller, M. (1993). *Visual Cues: Practical Data Visualization*. IEEE Computer Society.

[62] Kolacny, A. (1970). Kartographische Informationen–ein Grundbegriff und Grundterminus der modernen Kartographie. *Internationales Jahrbuch für Kartographie*, 10:186–193.

[63] Kolbe, T. (2020). 3D City DB. www.3dcitydb.org. Accessed: 28-05-2020.

[64] Kolbe, T. H. (2009). Representing and exchanging 3d city models with CityGML. In *Lecture Notes in Geoinformation and Cartography*, pages 15–31. Springer Berlin Heidelberg.

[65] Kurakula, V. (2007). A GIS-Based Approach for 3D Noise Modelling Using 3D City Models. mathesis, International Iinstitute for Geo-information Science and Earth Observation, Enschede.

[66] Kutzner, T., Chaturvedi, K., and Kolbe, T. H. (2020). CityGML 3.0: New Functions Open Up New Applications. *PFG Journal of Photogrammetry, Remote Sensing and Geoinformation Science*, 88(1):43–61.

[67] Kutzner, T. and Kolbe, T. (2018). CityGML 3.0: Sneak Preview. In *38. Wissenschaftlich-Technische Jahrestagung der DGPF und PFGK18 Tagung in München - Publikationen der DGPF*, volume 27.

[68] Lazar, J., Feng, J. H., and Hochheiser, H. (2017). *Research Methods in Human Computer Interaction*. Elsevier LTD, Oxford.

[69] Ledoux, H., Ohori, K. A., Kumar, K., Dukai, B., Labetski, A., and Vitalis, S. (2019). CityJSON: a compact and easy-to-use encoding of the CityGML data model. *Open Geospatial Data, Software and Standards*, 4(1).

[70] MA18, S. u. S. (2014). Smart City Wien - Rahmenstrategie. Technical report, Stadt Wien, Wien.

[71] MA18, S. u. S. (2016). Realnutzungskartierung 2016. data.wien.gv.at/Statistik - Realnutzungskartierung. Accessed: 25-05-2020.

[72] MA22, W. U. (2015). Urban Heat Islands - Strategieplan Stadt Wien. data.wien.gv.at/uhi-strategieplan. Accessed: 07-02-2020.

[73] MA23, Wirtschaft, A. u. S. (2020a). Lufttemperatur april 2018 bis april 2020. www.wien.gv.at/lufttemperatur. Accessed: 26-05-2020.

[74] MA23, Wirtschaft, A. u. S. (2020b). Statistik - aktuelle kennzahlen. data.wien.gv.at/Statistik - Aktuelle kennzahlen. Accessed: 25-05-2020.

[75] MA41, S. W. (2019). Geodaten. data.wien.gv.at/Geodaten. Accessed: 04-09-2019.

[76] MA41, S. W. (2020a). Geodatenviewer. www.wien.gv.at/Geodatenviewer. Accessed: 01-06-2020.

[77] MA41, S. W. (2020b). Solarpotenzial 3D - Stadtvermessung Wien. data.wien.gv.at/Solarpotenzial3D. Accessed: 29-05-2020.

[78] MA41, S. W. (2020c). Stadtplan 3D - Stadtvermessung Wien. data.wien.gv.at/Stadtplan3D. Accessed: 27-05-2020.

[79] MA5, F. (2011). Wien in zahlen 2011. Wien in Zahlen 2011. Accessed: 25-05-2020.

[80] MacEachren, A. M. and Kraak, M.-J. (2001). Research Challenges in Geovisualization. *Cartography and Geographic Information Science*, 28(1):3–12.

[81] Maronga, B., Gross, G., Raasch, S., Banzhaf, S., Forkel, R., Heldens, W., Kanani-Sühring, F., Matzarakis, A., Mauder, M., Pavlik, D., Pfafferott, J., Schubert, S., Seckmeyer, G., Sieker, H., and Winderlich, K. (2019). Development of a new urban climate model based on the model palm - project overview, planned work, and first achievements. *Meteorologische Zeitschrift*, 28(2):105–119.

[82] Mathieu, P.-P. and Aubrecht, C., editors (2018). *Earth Observation Open Science and Innovation*. Springer International Publishing.

[83] Mazza, R. (2009). *Introduction to Information Visualization*. Springer London.

[84] Mete, M. O., Guler, D., and Yomralioglu, T. (2018). Development of 3D Web GIS Application with open source library. *Selcuk University Journal of Engineering ,Science and Technology*, 6(Özel (Special)):818–824.

[85] Metral, C., Ghoula, N., Silva, V., and Falquet, G. (2014). *A repository of information visualization techniques to support the design of 3D virtual city models*, pages 175–194. Innovations in 3D Geo-Information Sciences. Springer, Instanbul. ID: unige:41916.

[86] Michael Djak, Sebastian Peyer, M. R. S. Z. (2017). Plan einer heuristischen evaluierung. courses.isds.tugraz.at/hci/reports/heolan–de.html. Accessed: 19-04-2021.

[87] Mirzaei, P. A. (2015). Recent challenges in modeling of urban heat island. *Sustainable Cities and Society*, 19:200 – 206.

[88] Moran, K. and Pernice, K. (2020a). Remote moderated usability tests: How to do them. www.nngroup.com/moderated-remote-usability-test. Accessed: 24-02-2021.

[89] Moran, K. and Pernice, K. (2020b). Remote moderated usability tests: Why to do them. www.nngroup.com/moderated-remote-usability-test-why. Accessed: 08-06-2021.

[90] Morrish, S. W. and Other, T. (n.d.). Point Clouds and 3D Mesh. https://proceedings.esri.com/library/userconf/proc17/tech-workshops/tw_677-236.pdf. Accessed: 22-06-2020.

[91] mr.doob (2020). three.js. https://github.com/mrdoob/three.js. Accessed: 19-06-2020.

[92] National Center of Atmospheric Research Staff (Eds). (NCAR) (2013). Common Climate Data Formats: Overview. https://climatedataguide.ucar.edu/climate-data-tools-and-analysis/common-climate-data-formats-overview. Accessed: 24-08-2021.

[93] Nielsen, J. (1992). Finding usability problems through heuristic evaluation. In *Proceedings of the SIGCHI conference on Human factors in computing systems - CHI 92*. ACM Press.

[94] Nielsen, J. (1994a). How to conduct a heuristic evaluation. https://www.nngroup.com/How to Conduct a Heuristic Evaluation. Accessed: 16-02-2021.

[95] Nielsen, J. (1994b). *Usability Engineering*. Elsevier LTD, Oxford.

[96] Nielsen, J. (1994c). *Usability inspection methods*. Wiley, New York.

[97] Nielsen, J. and Phillips, V. L. (1993). Estimating the relative usability of two interfaces. In *Proceedings of the SIGCHI conference on Human factors in computing systems - CHI 93*. ACM Press.

[98] Nielson, G. M. and Hamann, B. (1990). Techniques for the interactive visualization of volumetric data. In *Proceedings of the First IEEE Conference on Visualization: Visualization 90*. IEEE Comput. Soc. Press.

[99] Nivala, A.-M., Brewster, S., and Sarjakoski, T. L. (2008). Usability evaluation of web mapping sites. *The Cartographic Journal*, 45(2):129–138.

[100] N.N. (2019). CityGML 3.0 Conceptual Model. github.com/opengeospatial/CityGML-3.0CM. Accessed: 26-11-2019.

[101] Norris, J. (2015). Future trends in geospatial information management: the five to ten year vision. Technical report, United Nations - Committee of Experts on Global Geospactial Information Management.

[102] Oke, T. R. (2005). Towards better scientific communication in urban climate. *Theoretical and Applied Climatology*, 84(1-3):179–190.

[103] Open Geospatial Consortium (2012). OGC city geography makrup language (citygml) encoding standard 2.0.0. Technical report, Open Geospatial Consortium.

[104] Patz, J., Campbell-Lendrum, D., Holloway, T., and A Foley, J. (2005). Impact of Regional Climate Change on Human Health. *Nature*, 438:310–317.

[105] Plaisant, C. (2004). The challenge of information visualization evaluation. *Proceedings of the working conference on Advanced visual interfaces*, pages 109–116.

[106] PlanSinn Planung & Kommunikation GmbH (2019). Lila4Green. www.lila4green.at. Accessed: 02-01-2020.

[107] Poulain, P. (2018). Community Experiments with Time-Dynamic 3D Tiles. https://cesium.com/blog/2018/11/08/weather-prediction-data-time-series-and-3d-tiles/. Accessed: 29-06-2020.

[108] Poulain, P. (2019). Illustation of changes in temperature near surface during a hot day. youtube.com/pascalepoulain. Accessed: 10-12-2019.

[109] QGISproject (2020). QGIS User Guid - Working with Mesh Data. docs.qgis.org/QGISUserGuide/WorkingwithMeshData. Accessed: 17-06-2020.

[110] Qin, Z., McCool, M. D., and Kaplan, C. (2008). Precise vector textures for real-time 3D rendering. In *Proceedings of the 2008 symposium on Interactive 3D graphics and games - SI3D 08*. ACM Press.

[111] Quiñones, D. and Rusu, C. (2017). How to develop usability heuristics: A systematic literature review. *Computer Standards & Interfaces*, 53:89–122.

[112] Quiñones, D., Rusu, C., and Rusu, V. (2018). A methodology to develop usability/user experience heuristics. *Computer Standards & Interfaces*, 59:109–129.

[113] Santamouris, M. (2014). Cooling the cities – A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. *Solar Energy*, 103:682–703.

[114] Scherer, D., Ament, F., Emeis, S., Fehrenbach, U., Leitl, B., Scherber, K., Schneider, C., and Vogt, U. (2019a). Three-dimensional observation of atmospheric processes in cities. *Meteorologische Zeitschrift*, 28(2):121–138.

[115] Scherer, D., Antretter, F., Bender, S., Cortekar, J., Emeis, S., Fehrenbach, U., Gross, G., Halbig, G., Hasse, J., Maronga, B., Raasch, S., and Scherber, K. (2019b). Urban climate under change [uc]2 ? a national research programme for developing a building-resolving atmospheric model for entire city regions. *Meteorologische Zeitschrift*, 28(2):95–104.

[116] Shepherd, I. D. H. (2008). Travails in the third dimension: A critical evaluation of three-dimensional geographical visualization. In *Geographic Visualization*, pages 199–222. John Wiley & Sons, Ltd.

[117] Shneiderman, B. (2014). The Big Picture for Big Data: Visualization. *Science*, 343(6172):730–730.

[118] Sporer, T., Weiß, D., Giesz, M., and Striegl, H. (2005). Evaluation des audiovisuellen digitalen informationsdienstes von knowledgebay. pages 399–410.

[119] Stadt Wien (2016). Klimaszenarien für das Bundesland Wien bis 2100. data.wien.gv.at. Accessed: 26-05-2020.

[120] Stadt Wien (2019). Open Government Data. data.wien.gv.at. Accessed: 03-09-2019.

[121] Stadt Wien (2020a). Cooles Wien - Aktuelle Maßnahmen gegen Hitzeinseln und Klimawandel. www.data.wien.gv.at/CoolesWien. Accessed: 26-05-2020.

[122] Stadt Wien (2020b). Stadtentwicklung - Wiener Hitzekarte. www.data.wien.gv.at/Hitzekarte. Accessed: 26-05-2020.

[123] Stadt Wien (2020c). Stadtentwicklung - Wiener Stadtklimaanalyse als Grundlage für Planungsprojekte. https://www.wien.gv.at/stadtentwicklung/grundlagen/stadtforschung/stadtklimaanalyse. Accessed: 28-06-2021.

[124] Stähli, L. (2017). Cesium vs. ArcGIS API for JavaScript. http://www.ika.ethz.ch/studium/cartography_lab/staehli_report.pdf. Accessed: 10-07-2020.

[125] Stahre Wästberg, B., Tornberg, J., Billger, M., Haeger-Eugensson, M., and Sjöberg, K. (2013). How to visualize the invisible simulating air pollution dispersions in a 3D city model. In *13th International Conference on Computers in Urban Planning and Urban Management, CUMPUM 2013; Utrecht; Netherlands; 2 July 2013 through 5 July 2013*.

[126] Stone, D., Jarrett, C., Woodroffe, M., and Minocha, S. (2005). *User Interface Design and Evaluation*. Elsevier Science & Technology.

[127] Tomlinson, R. F. (1969). A Geographic Information System for Regional Planning. *Journal of Geography (Chigaku Zasshi)*, 78(1):45–48.

[128] Tory, M., Kirkpatrick, A. E., Atkins, M. S., and Möller, T. (2006). Visualization task performance with 2D, 3D, and combination displays. *IEEE Transactions on Visualization and Computer Graphics*, 12(1):2–13.

[129] Tory, M. and Moller, T. (2005). Evaluating visualizations: do expert reviews work? *IEEE Computer Graphics and Applications*, 25(5):8–11.

[130] Trubka, R., Glackin, S., Lade, O., and Pettit, C. (2016). A web-based 3D visualisation and assessment system for urban precinct scenario modelling. *ISPRS Journal of Photogrammetry and Remote Sensing*, 117:175–186.

[131] United Nations, Department of Economic and Social Affairs, Population Division (2015). World Population Prospects: The 2015 Revision, Key Findings and Advance Tables. *working paper no. ESA/P/WP*, 241.

[132] United Nations, Department of Economic and Social Affairs, Population Division (2018). World Urbanization Prospects: The 2018 Revision, KeyFacts.

[133] University Corporation for Atmospheric Research (2019). Network Common Data Form (NetCDF). `https://www.unidata.ucar.edu/software/netcdf/`. Accessed: 05-09-2019.

[134] Unrau, R. and Kray, C. (2018). Usability evaluation for geographic information systems: a systematic literature review. *International Journal of Geographical Information Science*, 33(4):645–665.

[135] van Oosterom, P. and Stoter, J. (2010). 5d data modelling: Full integration of 2d/3d space, time and scale dimensions. In *Geographic Information Science*, pages 310–324. Springer Berlin Heidelberg.

[136] Vion-Dury, J.-Y. and Santana, M. (1994). Virtual images. In *Proceedings of the ninth annual conference on Object-oriented programming systems, language, and applications - OOPSLA*. ACM Press.

[137] virtualcitySYSTEMS GmbH (2019). CityGML. www.virtualcitysystems.de. Accessed: 26-11-2019.

[138] Väätäjä, H., Varsaluoma, J., Heimonen, T., Tiitinen, K., Hakulinen, J., Turunen, M., Nieminen, H., and Ihantola, P. (2016). Information visualization heuristics in practical expert evaluation. In *Proceedings of the Beyond Time and Errors on Novel Evaluation Methods for Visualization - BELIV '16*. ACM Press.

[139] Ward, M. (2015). *Interactive data visualization : foundations, techniques, and applications*. An A K Peters book. CRC Press, Boca Raton, Fla. [u.a.], 2. ed.. edition.

[140] Ware, C. and Franck, G. (1996). Evaluating stereo and motion cues for visualizing information nets in three dimensions. *ACM Transactions on Graphics*, 15(2):121–140.

[141] Weisstein, E. W. (2020). Mathworld–A Wolfram Web Resource. https://mathworld.wolfram.com/Sphere.html. Accessed: 24-06-2020.

[142] Williams, R., Scholtz, J., Blaha, L. M., Franklin, L., and Huang, Z. (2018). Evaluation of visualization heuristics. In *Human-Computer Interaction. Theories, Methods, and Human Issues*, pages 208–224. Springer International Publishing.

[143] Wittner, E. (2020). CityGML to I3S: Streaming fast 3D city data in ArcGIS. https://www.esri.com/arcgis-blog/products/arcgis/3d-gis/citygmlbuildingstoi3s/. Accessed: 18-06-2021.

[144] ZAMG (2013). FOCUS-I. www.zamg.ac.at/klima/klimaforschung/stadtklima/focus-i. Accessed: 08-06-2020.

[145] ZAMG (2019). Stadtklima. www.zamg.ac.at/klima/klimaforschung/stadtklima. Accessed: 30-12-2019.

[146] ZAMG (2020). Klimadaten von österreich 1971 - 2000. www.zamg.ac.at/Klimadaten. Accessed: 26-05-2020.

[147] Zlatanova, S. (2000). *3D GIS for urban development*. PhD thesis, Netherlands. ITC Dissertation; 69. PhD thesis Graz University of Technology; Summaries in English, German and Bulgaria.

[148] Zuk, T., Schlesier, L., Neumann, P., Hancock, M. S., and Carpendale, S. (2006). Heuristics for information visualization evaluation. In *Proceedings of the 2006 AVI workshop on BEyond time and errors novel evaluation methods for information visualization - BELIV 06*. ACM Press.

[149] Zuvela-Aloise, M., Wit de, R., Hollosi, B., and Andre, K. (2017). Urban Modelling - wissenschaftliche Basis klimasensitiver Stadtplanung. zamg.ac.at/Stadtklima/UrbanModelling. Accessed: 25-05-2020.

A GUIDELINE USED WITHIN THE EXPERT INTERVIEW OF THE HEURISTIC EVALUATION

This chapter shows the guideline 'Heuristische Evaluierung von 3d Visualisierungsansätzen - Anwender, Anforderungen und Checklistet', which was provided for the evaluators during the expert interview of the HE.

ANWENDER UND ANFORDERUNGEN

Anwender von 3d visualisierten Lufttemperaturdaten in 3d Stadtmodellen:

Politische Entscheidungsträger

Stadtplaner

Zivilbevölkerung

Laut Literatur werden mittels 3d Stadtmodellen Informationen transportiert, die Entscheidungsprozesse unterstützen oder Monitoring-Ergebnisse abbilden. Bei Visualisierung von 'Big Data' bzw. komplexen Datensätzen wird oftmals das Augenmerk auf Beziehungen der Daten zueinander, Muster innerhalb der Daten, sowie Freiräume oder Ausreißer gelegt. Stadtklimaanalysen fokussieren auf das Ablesen von bestimmten Temperaturwerten, Erkennen von Zusammenhängen und das Erkennen von Clustern (z.B. Wärmeinseln).

Anforderungen an 3d visualisierte Lufttemperaturdaten in 3d Stadtmodellen:

1. *Ablesen von Temperaturwerten innerhalb des Models.*
2. *Erkennen von Mustern bzw. Clustern innerhalb der Temperaturwolke* (z.B. Wärmeinseln).
3. *Ablesen von Zusammenhängen* (z.B. niedrigere Temperaturen über unverbauten Gebiet).
4. *Überschreiten von bestimmten Temperaturwerten* (z.B. Sommertag 25°C oder Tropennacht 20°C).

CHECKLIST

Heuristiken mit Fokus auf Visualisierung von 3d Geodaten sowie Interaktion innerhalb des Modells.

o *Informationsvisualisierung* — Gibt es Probleme hinsichtlich der Visualisierung der Informationen: Sind die gewählten *Symbole* hinsichtlich Form und Größe adäquat für die Datenrepräsentation? Sind die *Farben* geeignet um die Dateninformation zu transportieren. Verursachen die gewählten Farben Wahrnehmungsschwierigkeiten? Verursacht die Geländeoberflächen*texturierung* Probleme in der Wahrnehmung der Lufttemperaturdaten? Verursacht die *Auflösung* von Oberflachtextur, Lufttemperaturdaten Probleme im Bezug auf die Informationswahrnehmung?

o *Räumliche Wahrnehmung und Orientierung* — Gibt es Probleme hinsichtlich der Räumlichen Wahrnehmung und der Orientierung. Ist es möglich aus visualisierten Information *Höhenwerte* abzulesen? Können Distanzen zwischen den visualisierten Punkten wahrgenommen werden? Können Sie sich im Datenraum gut orientieren?

o *Ästhetik und minimales Design* — Gibt es Probleme beim Visuellen Layout hinsichtlich der Ästhetik? Gibt es Probleme im Zusammenhang mit fehlendem 'White Space' und überflüssigen bzw. unnötigen Elementen?

o *Interaktivität und Intuitivität* — Treten bei der Interaktion mit dem Modell Probleme auf? Ist der Visualisierungsansatz intuitiv? Welche Probleme stehen damit im Zusammenhang?

o *Sonstige* — Welche weiteren Probleme können noch angeführt werden.

B GENERALIZED WORKFLOWS OF THE IMPLEMENTATION PROCESSES

WORKFLOW VA1

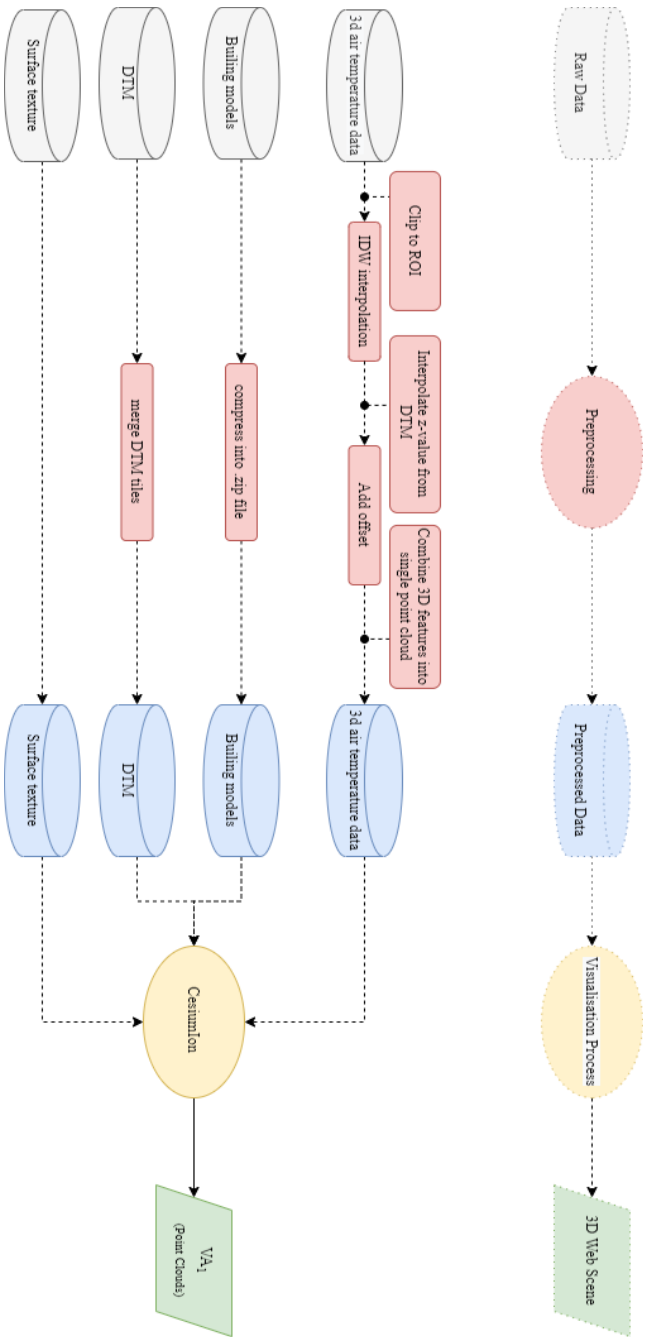


Abbildung B.1: Generalized workflow of the implementation process of VA_1 [own figure].

WORKFLOW VA2 AND VA3

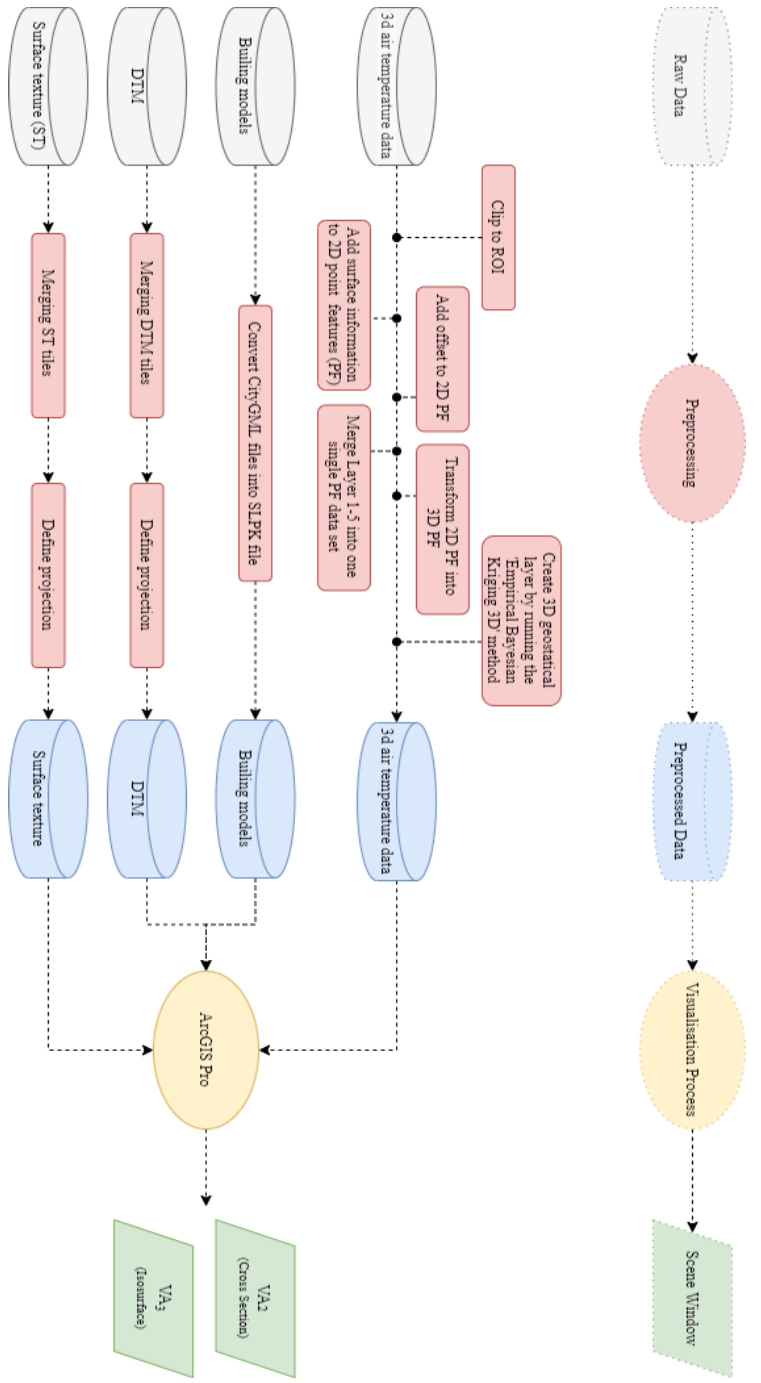


Abbildung B.2: Generalized workflow of the implementation process of VA_2 and VA_3 [own figure].

COLOPHON

This document was typeset using LaTeX. The document layout was generated using the `arsclassica` package by Lorenzo Pantieri, which is an adaption of the original `classicthesis` package from André Miede. The figures were mostly drawn using `draw.io`.