Game engine based spatial support system for urban development design.

Siebren Meines
student #4880412

1st supervisor: Azarakhsh Rafiee
2nd supervisor: Eleonora Brembilla
January 16, 2023

1. Introduction

With increasing weather extremities due to climate change, and the densification and expansion of our urban environments, the need to consider environmental factors such as natural light is becoming increasingly important. Natural light plays a critical role in human health and well-being, but also significantly impacts the energy efficiency and sustainability of buildings as well as its impact on the visual appeal and liveability of a city

One of the most notable benefits of natural light is its impact on human health. The exposure to natural light can improve sleep patterns, reduce stress and anxiety, and even boost mood and productivity (Bertani et al., 2021). Natural light also has a positive impact on the visual appeal and liveability of urban environments. High levels of artificial lighting and lighting-pollution can have negative effects on human well-being, such as disturbance of rhythm and negatively affecting one's ability to sleep (Chepesiuk, 2009). In urban environments, where residents may be at greater risk of light deficiency due to the prevalence of artificial lighting and limited access to the outdoors, incorporating natural light into the development of buildings can help to improve the health and well-being of residents. In contrast to artificial light, which can create harsh, uneven lighting conditions, natural light is softer and more diffuse, creating a more pleasant and inviting atmosphere (*Natural Light Is Fundamentally Different Than Artificial Light*, 2017). In addition to its benefits for human health, natural light can also play a crucial role in the energy efficiency and sustainability of buildings. Natural light can reduce the need for artificial lighting, which in turn can reduce energy consumption and greenhouse gas emissions.

However, integrating natural light into urban development is not without its challenges. One key challenge is the need to consider the changing nature of natural light throughout the day and throughout the year. To maximize the benefits of natural light, urban developers must consider the position of the sun and the at various times of the day and in different seasons. This can be particularly complex in urban environments, where the density and height of buildings can create significant shading effects.

Another challenge is the need to balance the benefits of natural light with other development considerations, such as energy efficiency. For example, incorporating large windows into the development of buildings can increase the availability of natural light, but it can also reduce the building's ability to retain heat in the winter. On the other hand, in the summer natural light can contribute to the urban heating island effect (UHI), this is particularly problematic in environments with reflective surfaces, such as concrete and glass (Sen & Khazanovich, 2021). Both these scenarios lead to higher energy costs.

To address these challenges, urban developers must carefully consider the trade-offs between for incorporating natural light in a way that maximizes its benefits while minimizing potential drawbacks. As an answer to these challenges, there are a range of strategies that cities can use to effectively incorporate natural light into urban development. One key approach is the use of passive solar development, which involves orienting buildings and windows in such a way as to maximize the amount of natural light that enters the building (Wikipedia contributors, 2022). This can be achieved through the consideration of the orientation and placement of buildings, as well as the use of light-reflecting or absorbing materials, the use of strategic window placement, skylights, and other development elements that allow natural light to enter the building while minimizing energy loss. Besides passive solutions, there are also models that can calculate amount of natural light in urban areas, like ladybug which urban planners and architects use in grasshopper.

While passive solutions to optimize natural lighting in urban areas can be effective, the problem is to complex and multisided to be solves passively. Instead, models and calculations should be used to have the optimal amount of natural lighting in urban areas. This thesis will seek to provide a solution to urban developers and architects to integrate light simulation in the design process. The thesis will aim to develop a game engine based spatial decision support system (SDSS) for urban development. The tool aims to provide urban developers an easy, scientific, and comprehensible tool to make spatial decisions considering different criteria, with the initial focus on natural light and urban density factors. The tool will combine urban decision-making with GIS analysis. The efficient use of geospatial data and GIS functions will support a scalable architecture for urban development. A game engine will be used to make the tool interactive, to be able to quickly (re)calculate spatial analysis, and to make it fit for VR.

2. Related work

The related work section presents previous research that is closely related to the topic of this thesis. This provides context for the current study and highlights any gaps in the existing literature that the current study aims to address or combine.

2.1 3D spatial analysis tools for urban development

To understand the possibility for the development of a web-based solar potential tool for urban development, this section describes some urban development tools with integrated (3D) GIS/analysis capabilities.

ArcGIS Urban (Urban Planning & Design-Smart City Planning | ArcGIS Urban, n.d.) is a cloud-based solution that provides a range of tools and features that allow users to manage, analyse, and visualize spatial data related to urban environments, as well as collaborating with other stakeholders. The software also includes several pre-built templates and workflows that can help users quickly and easily create maps and reports. One of the key features of ArcGIS Urban is its ability to integrate with other Esri products, such as CityEngine (Fabricius, 2021), and third-party data sources. This allows users to easily incorporate data from a variety of sources into their analysis and visualization projects. Some of its key features are:

- Create and manage 3D models of urban environments
- Importing and organizing data from various sources and scales, including demographic, land use, transportation, and infrastructure data on regional, city, neighbourhood and building data.
- Analysing spatial patterns and trends in urban data, including spatial analysis techniques such as network analysis.

- Visualizing data through maps, diagrams, and other spatial representations.
- Modelling and simulating urban growth and change over time.
- Generating reports and presentations to communicate findings and recommendations.
- Create custom tools and apps to support urban planning and analysis processes.

3D Cityplanner (Strategis Groep bv, n.d.) is a 3D software application that can be used in a browser. It can calculate and visualize aspects such as land use, sustainability, and finances. Other than ArcGIS Urban, which has a separate design tool (CityEngine), 3D Cityplanner integrates design and calculations. Users can upload their own GIS data or use some of the standard features from 3D Cityplanner. Another difference with ArcGIS urban is that it allows users to automatically generate buildings given certain inputs.
The main functionalities of 3D Cityplanner are:

- Import and integrate different types of 3D building models, such as BIM, SketchUp, or CityGML.
- Use the automatic building generator feature to create complex apartment buildings and other structures quickly and easily.
- 4D project planning functionality to not only visualize your design in 3D, but also to simulate and track the progress of construction over time.
- Minimize noise hindrance by using the built-in tools to analyse and mitigate potential noise issues.
- Create and share interactive dashboards online with stakeholders.

Other tools for urban development, but that do not include the possibility of the generation or calculation of 3D GIS data are:

- 3D GIS from Sivan Design (3D GIS in the Cloud, 2022).
- City2Gether (City2Gether | Smart Citizen, n.d.)
- AT&T Smart city solutions (*Smart City Technology and IoT Solutions At*, n.d.)

Although ArcGIS Urban and 3D Cityplanner both have a variety of capabilities, they are lacking on 3D analysis, like light analysis. Besides that, both platforms are limited in customisation and require payment.

2.2 3D City Models

3D city models represent the physical characteristics of a city in 3D, including buildings, roads, bridges, trees, and other infrastructure. They can be used for a variety of applications, including emergency response, traffic management, and urban development.

The main benefit of 3D city models is their ability to provide a more accurate and comprehensive representation of a city compared to traditional 2D maps. By adding a third dimension, these models can more accurately capture the shape, height, and geometry of buildings, as well as the location and orientation of streets and other infrastructure. This is particularly important for analysis that are depending on the geometry of a building, such as noise, solar/light and volumetric analysis (Biljecki et al., 2016). Based on the acquisition technique and the intended usage, 3D city models can be created in various levels of detail (LOD). These LOD determine the level of abstraction of the model, as seen in figure 1.

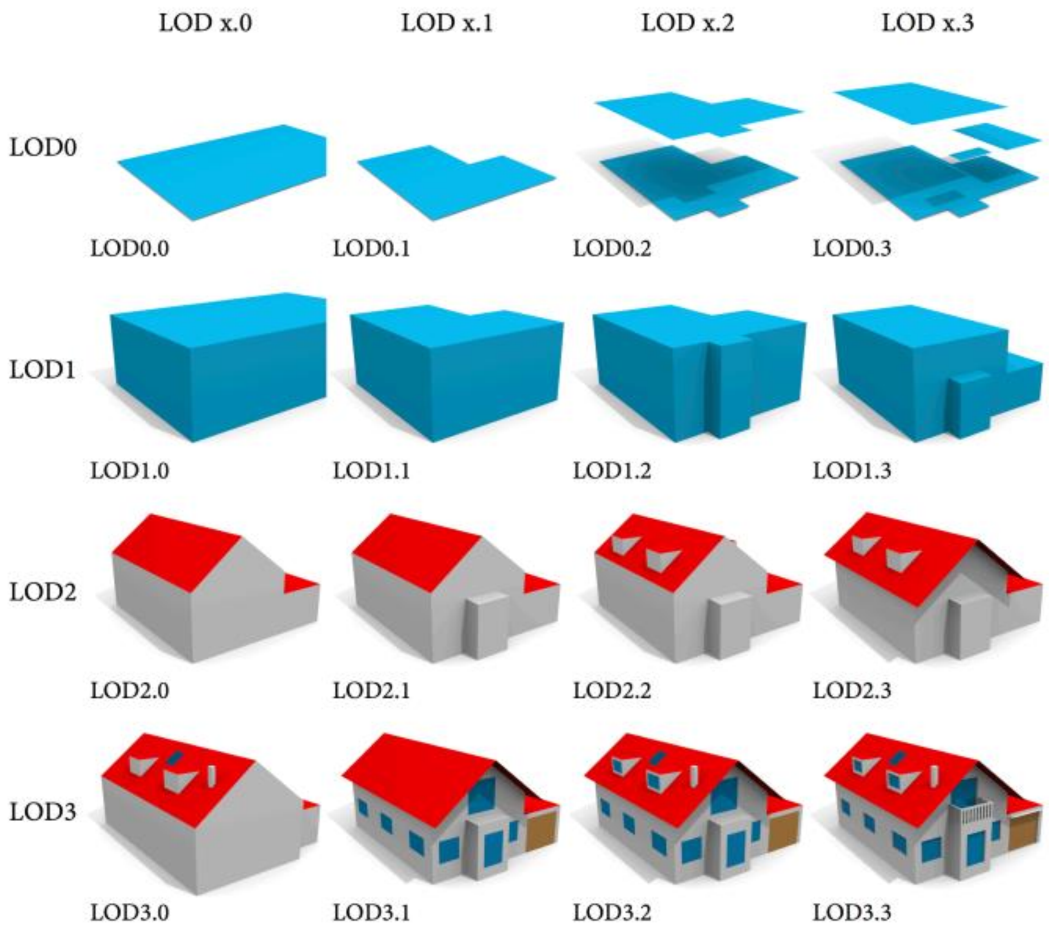

Figure 1. Different LOD of 3D city models.

Despite their benefits, there are also challenges associated with the creation and maintenance of 3D city models. Some of these challenges are:

- Standardization. 3D models are often generated independently, using different base data and reconstruction software. Furthermore, there is a lack of standardization in terms of geometry and semantics (*State of the Art in 3D City Modelling*, 2022).
- Data interoperability. Due to the lack of standardization, it is also difficult to convert one data model into another format (*State of the Art in 3D City Modelling*, 2022).
- Data quality. Most openly available 3D city models have geometric and topological errors: missing surfaces, self-intersecting volumes, duplicate vertices. (Biljecki et al., 2016).
- Data governance.

- Cost. Currently most approaches of generating and maintaining 3D city models are cost and labour intensive (Steinhage, Behley, Meisel & Cremers, 2010).
- Urban analyses. There is a need for standardization or toolkits for simulation, analyses, and management (Billen et al. 2015)

An example of a 3DCity model is CityJSON. CityJSON is a JSON (JavaScript Object Notation) based and standardized data exchange format for 3D city models (*CityJSON*, n.d.). JSON is a common data interchange format that is easy to read and write for both humans and machines. CityJSON is the official standard of the Open Geospatial Consortium (*The Home of Location Technology Innovation and Collaboration* | *OGC*, n.d.). CityJSON is designed to be lightweight, extensible, and easy to use, making it a suitable for storing, exchanging, and visualizing 3D city models. It includes support for complex geometry, metadata, and attributes, which allows users to store and visualize detailed and accurate information about the city and its features.

2.3 Digital twins

A digital twin is "a virtual representation of a physical system (and its associated environment and processes) that is updated through the exchange of information between the physical and virtual systems." (VanDerHorn, & Mahadevan, 2021). The main difference between a 3D Model and a digital twin is that a digital twin dynamically updates using an evolving data set related to the object of which it forms a digital twin (Wright, & Davidson, 2020). Digital twins are being used in a variety of industries, from manufacturing to healthcare and urban development. With the help of digital twins, cities can be managed more efficiently and sustainably, and urban planners can more accurately predict and plan future needs.

Digital twins consist of four main components, as seen in figure 2: physical environment, virtual environment, data environment, analytical environment, connectivity (Grübel et al., 2022). The physical environment is the real-world environment which is virtually represented in the virtual environment using the raw data from the data environment. The analytics environment is used to process the data and generate insights. The connection, if performed correctly makes for interoperability between different digital twins. As figure 3 shows, a digital twin can form the foundation of a Smart City. A Smart City is a technological approach to resolve urban issues using bench-marking indicators on topics such as economic, governmental, social, and environmental issues (Grübel et al., 2022).

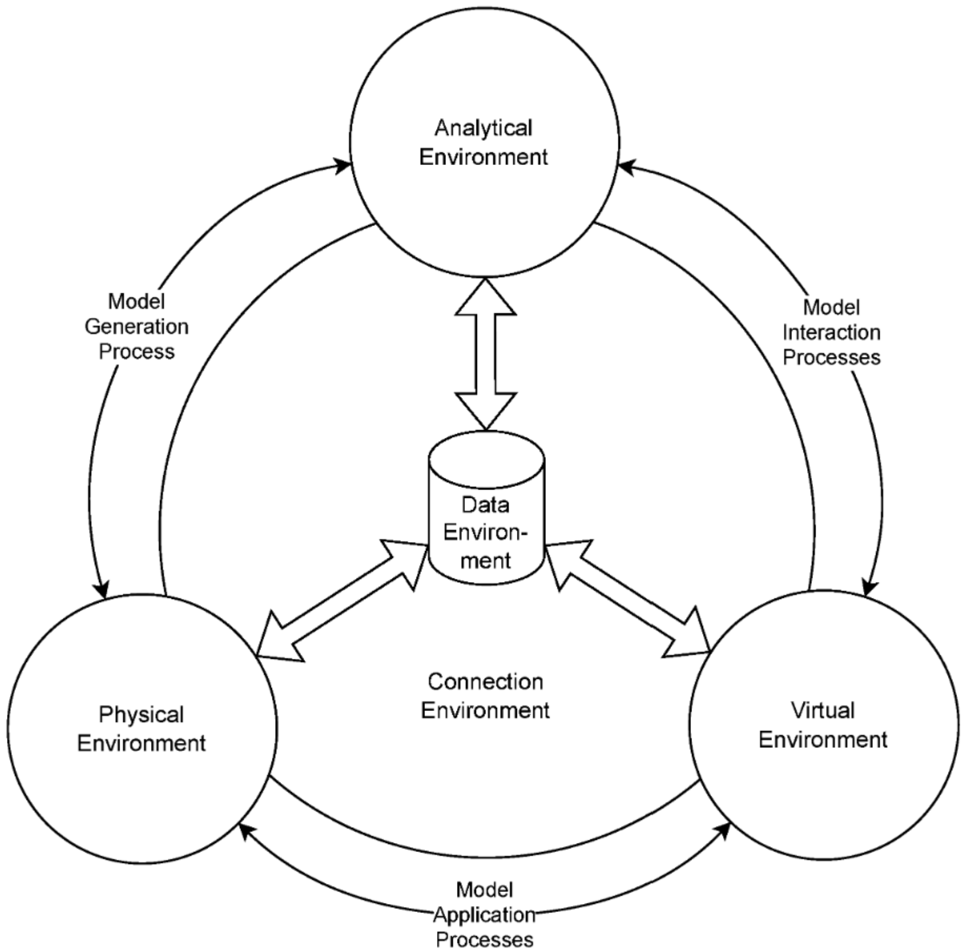

Figure 2. Four main components of digital twins (Grübel et al., 2022).

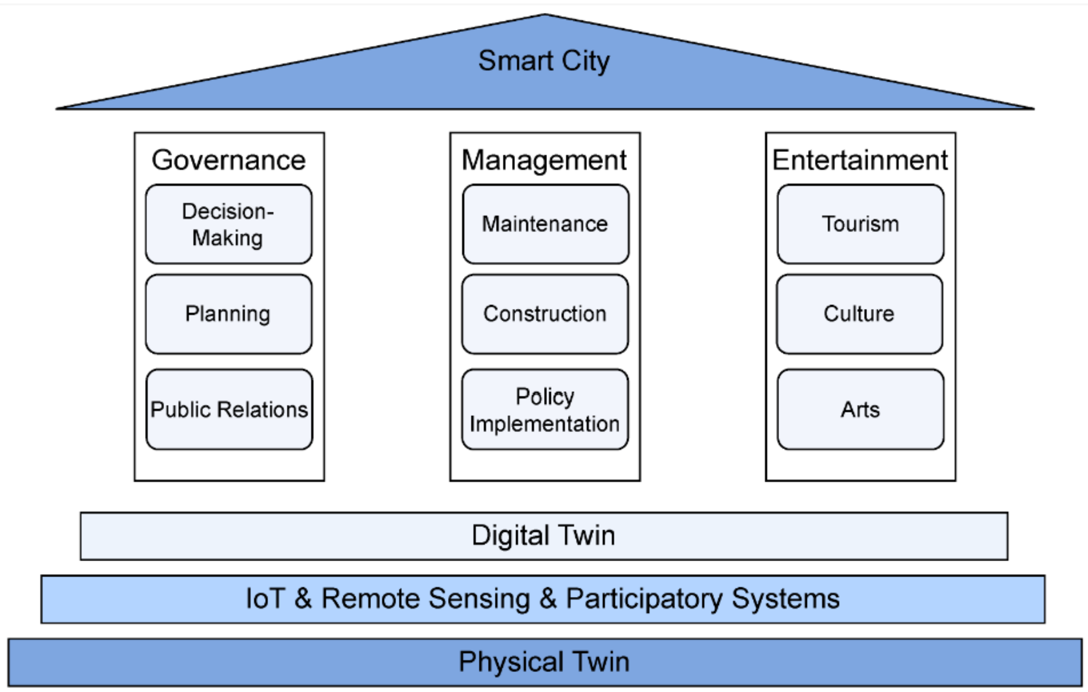

Figure 3. Digital twin as the foundation of a smart city (Grübel et al., 2022).

Digital twins allow for real-time monitoring and analysis of existing urban systems, simulate the effects of proposed changes to the physical environment. This could make it easier for urban developers to make informed decisions from multiple sources such as traffic patterns, air quality, and energy consumption. However, for a digital twin to be useful for the city, it should conform to the following rules (Lehtola et al. 2022).

- Follow the needs of the city. The digital twin should change and adapt based on the current and future needs of the city.
- Support for both high and low level of detail content. To allow for abstraction and analysis on different resolutions, the digital twin should have support for varying LOD.
- Automatic updating. A digital twin is a digital replication of a physical environment. If the physical environment changes, the digital twin should be automatically updated.
- Human perspective. The digital twin should be made in a way that it encourages information sharing and decision-making.

2.4 VR for urban development

Virtual reality (VR) technology has been increasingly utilized in the field of urban design as a tool for visualizing and assessing design proposals. VR allows designers

Feature	**Benefits**
Freedom of design	The freedom of the design allows VR media to be used in any planning scenario and in particular to create more variants compared to conventional planning processes
Adaptivity	Individual planning variants can be easily created by using parameters. Specific details of planning variants can also be investigated by changing the focus of the VR scenario
Sensor-motor manipulation	Sensor-motor Manipulation is not a feature commonly encountered in planning processes. However, it can be useful to validate the handling of objects or the spatial interactions with objects, for example if a door can be opened easily or if a staircase offers sufficient space for a two-person passage
Reproducibility	Reproducibility ensures that a variant can be validated over and over again, for example to increase the decision-making reliability of a citizen participating in the planning process
Standardization	Standardization allows adopting defined solutions from other contexts, for example by means of a component library, and test them as variants
Presence	Presence ensures that attention is focused to a large extent on the variants being evaluated or on the solution being designed. Collaborative scenarios may also support interaction between citizens
Privacy	If necessary, the planning variants may also be evaluated without impairing the public and—vice versa—the public not being aware of the evaluation
Reduction of risks and costs	The use of VR scenarios lowers the costs compared to real scenarios and renders the creation of physical models largely redundant. The dangers of real on-site inspections are also reduced, for example in road traffic or during inspections of facilities being planned, such as wastewater treatment plants

to experience and interact with a virtual environment as if they were physically present, providing a more immersive and realistic representation of the proposed design. To make VR compatible for web browsers, and to make the technology more accessible, WebVR was created. The WebXR Device API is an API that was developed as the next generation of WebVR which provides functionality for both AR and VR to the web (*Fundamentals of WebXR - Web APIs | MDN*, 2022). Zender et al. (2019) describe the possible benefits of using VR in figure 4.

Figure 4. Potential benefits of VR in urban development.

Other benefits of using VR for urban development are: (Jamei, Mortimer, Seyedmahmoudian, Horan & Stojcevski, 2017).

- Capability to assess design ideas in real time and within a 3D space during the design and planning phase.
- Effective communication among different stakeholders, academics, planning professionals, and communities.
- Saving of a significant amount of time by excluding guesswork in design.
- Integration of all aspects in the design and, thus, achieving a resilient sustainable city design with the least amount of time/funds; and
- Promotion of participatory planning.

Despite the benefits there are also challenges in the implementation of VR for urban development, of which the key challenge is cost (Jamei et al.,2017).

2.5 Game engines

Game engines are software frameworks designed to support the development of video games. These engines provide a range of tools and features that allow developers to create interactive 3D environments and gameplay mechanics. Historically game engines were designed for the development of video games. These engines provide a range of tools and features for designers to build interactive 3D environments and characters. However, game engines are not just suitable for the creation of games. The ability to use geospatial data in game engines to quickly create 3D environments and prototypes in those environments, makes it viable for the implementation in geodata related applications, such as urban development (Keil et al., 2021)

Examples of the implementation of game engines for geospatial related topics include:

- The Generation of 3D terrains or DEMs (Mat et al.).
- The recreation historical towns in VR (Kersten et al.).
- Solar potential assessment (Buyuksaliha, 2017).
- Quick prototyping of spatial layouts and building design (Edler, 2020).
- Safety training in dangerous environments such as underground hazard safety training (Liang, 2019).
- Application of physical models for environmental simulation (Edler, 2019).

2.6 Light analysis

Light analysis is an important aspect of urban environments, as it impacts the quality of life and well-being of individuals living in these areas. Some researchers argue that a lab is required for optimal light simulation, however, this is usually expensive to set up (Chen et al., 2019). Instead of using a physical environment for light analysis, computer models can also be used for the simulation of light. Most light simulation models are based on stochastic models. Research from Chen et al. (2019) suggests that VR lighting environments are the best way to represent physical light environments and that they can present different lighting attributes such as diffuse/glaring, bright/dim, open/close noisy/quiet, coherently with physical environments. Michelangelo et al. (2020) conclude that the combination of VR and the game engine Unreal are suitable for lighting design.

In solar simulation models there are 2 main concepts that are being applied: raytracing and Monte-Carlo simulation. Raytracing is a computer simulation method that uses geometric optics to model the path of light through a scene. It is commonly used to visualize the appearance of objects in a virtual environment, as well as to analyse the distribution of light in a space (Glassner, 1989). Raytracing is widely used in the field of lighting design and urban development to predict the illuminance levels and luminance distributions in outdoor and indoor spaces. One of the main advantages of raytracing is its ability to accurately model the interactions of light with surfaces and materials, which allows designers to predict the appearance of a space under different lighting conditions.

Monte Carlo is a computer simulation method that relies on random sampling to calculate the probability of different outcomes (Mooney, 1997). It can be used to analyse the distribution of light in urban environments by simulating the path of individual photons of light as they bounce off different surfaces. Monte Carlo simulations can accurately predict the distribution of light in complex environments, such as urban canyons, including the effects of reflections, refractions, and scatterings (Wang, 2014).

A commonly used method for simulation of daylight is Radiance. Radiance consists of a hybrid of deterministic raytracing and Monte Carlo simulation(*Radiance — Radsite*, n.d.). Brembilla, & Mardaljevic (2019) compared 5 Radiance based daylight simulation implementations. They concluded that there is a significant difference in the predicted annual sunlight exposure, with differences being of up to 39 percent points. Metrics that consider direct and inter-reflected light were found to have the best results.

3. Research question

This section states the research question and the sub-questions that will be used to answer that question. It will also elaborate on how these questions will be addressed.

The main research question is:

What is the best way to do an adaptive natural light analysis in a web-based VR environment developed with Unreal game engine?

The main question will be answered with the use of the sub-questions and will result into a methodology to integrate adaptive natural light analysis into an unreal web application, a comparison and benchmark of different light simulation models, a study of the usage of tools used by urban developers, and a web-based VR application developed using the Unreal game engine.

Sub questions:

- **How can 3D city models and light simulation models be integrated into an Unreal application?**

This question will be answered by a methodology to integrate 3D city models and light simulation models into Unreal. This methodology will then be applied in the Unreal application.

- **What kind of validation is there available for light data in the Netherlands, and how can this be used to benchmark light simulation methods in the Unreal application?**
  To compare different methods of light simulation, there must be a benchmark. This benchmark can consist of real-time weather data, or a previously validated dataset.

- **How do different methods of light simulation compare and perform in a web-based VR application build with Unreal?**
  This question will be answered by comparing 2-3 different methods of light simulation and how they perform based on certain criteria such as speed and accuracy.

- **How do urban developers use tools to make decisions in urban development and what kind of parameters do they use?**
  Depending on the availability of time this question will either be answered by a literature review, or by interviewing urban developers.

4. Methodology

This section provides the methodology of this research. It will present the steps that will be taken to complete the research. The steps are ranked in order, and in priority. The Moscow chart in chapter 5 is added to label the importance and prioritization of each step in the scope of this research.

4.1 Data collection

Initially a section of data will be downloaded from 3DBAG for the existing buildings. This will be done at LOD 2. This LOD is chosen because it has the details of the shape of the building, but not the complexity and size of the higher LODs. For the light data from KNMI will be used.

4.2 Build/set up the Game engine-based VR web-environment

After gathering the data, the game engine-based VR web-environment will be created using Unreal. This consists of the following steps:

1. Importing building data from 3DBAG.
2. Implementing VR into the application.
3. Launching the application to the web

4.3 Comparison of different light analysis methods vs. Benchmark

After setting up the application, 2 to 3 different solar simulation models will be applied and compared with a given benchmark. Due to the limited timeframe, there will not be a benchmark created in this study, instead a given benchmark will be used, by either using solar data from KNMI, or using a pre-validated benchmark dataset. These 2 to 3 different solar simulation methods will be compared both in literature review as well as in performance in the Unreal application.

4.4 User interaction

One important part of the application is to make it interactive for users. This allows users to remodel the urban design in the application and recalculate the spatial impact on the spot.

4.5 Further usability

While the initial focus of the application will be on solar simulations, the bigger goal of the development of this application is as a proof of concept for a SDSS for urban developers to make decisions considering different spatial and environmental criteria. Depending on the speed of the previous steps, further usability will be added to reinforce this proof of concept.

4.5.1 Zonal creation

The first extra feature that would be added is the ability to separate the buildings into different zones. This will allow users to group the buildings into different zones and with this the ability to calculate for different areas/buildings.

4.5.2 Density parameters

To expand the application into a SDSS and not a solely a spatial or environmental analysis tool it is important to integrate different criteria urban developers use to make decisions. Depending on the availability of time in the research, this part will be either based on literature research, or interviews with urban developers.

4.5.3 Further analysis/parameters

The last step of the application would be to add further spatial/environmental analysis. These would consist of noise and wind analysis.

4.6 Moscow chart

Figure 5. Moscow chart

5. Time planning

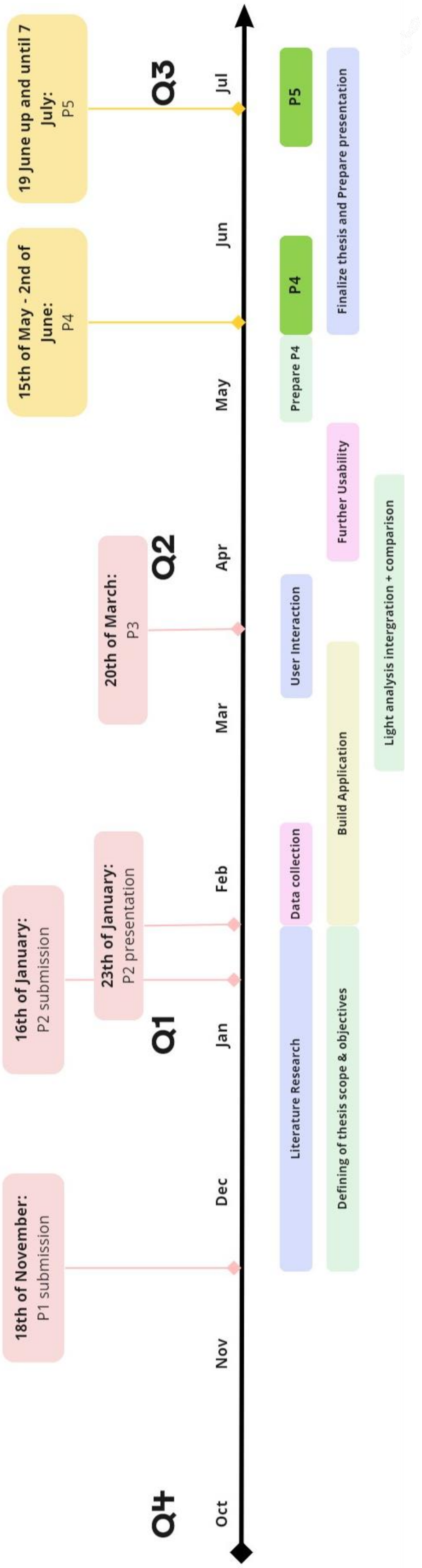

Figure 6. Time planning

6. Tools and datasets used

Tool	Usage
Programming languages: Python C++ Ubuntu	Unreal uses C++, solar packages such as ladybug have a python API. Radiance is available to use on a Linux terminal.
3DBAG downloader	As 3D city model a (partial) tile from 3DBAG will be used.
Unreal Game-engine	To develop the game engine-based VR web application Unreal will be used.

The datasets that will be used for this project consists of data about (day) light, which are accessible through KNMI. Besides that, 3DBAG will be used for the 3D city model.

7. References

3D GIS in the Cloud. (2022, February 16). Sivan Design. https://www.sivandesign.com/products/3dgis/

Bertani, D. E., De Novellis, A. M. P., Farina, R., Latella, E., Meloni, M., Scala, C., ... & Ferrari, S. (2021). “Shedding Light on Light”: A Review on the Effects on Mental Health of Exposure to Optical Radiation. *International journal of environmental research and public health*, *18*(4), 1670.

Biljecki, F., Ledoux, H., Du, X., Stoter, J., Soon, K. H., & Khoo, V. H. S. (2016). THE MOST COMMON GEOMETRIC AND SEMANTIC ERRORS IN CITYGML DATASETS. *ISPRS Annals of Photogrammetry, Remote Sensing & Spatial Information Sciences*, *4*.

Billen, R., Cutting-Decelle, A. F., Métral, C., Falquet, G., Zlatanova, S., & Marina, O. (2015). Challenges of semantic 3D city models: a contribution of the COST research action TU0801. *International Journal of 3-D Information Modeling (IJ3DIM)*, *4*(2), 68-76.

Brembilla, E., & Mardaljevic, J. (2019). Climate-Based Daylight Modelling for compliance verification: Benchmarking multiple state-of-the-art methods. *Building and Environment*, *158*, 151-164.

Chen, Y., Cui, Z., & Hao, L. (2019). Virtual reality in lighting research: Comparing physical and virtual lighting environments. *Lighting Research & Technology*, *51*(6), 820-837.

Buyuksaliha, G., Bayburta, S., Baskaracaa, A. P., Karimb, H., & Rahmanb, A. A. (2017). Calculating solar energy potential of buildings and visualization within unity 3D game engine. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *42*(4/W5).

Chepesiuk, R. (2009). Missing the dark: health effects of light pollution.

City2Gether | Smart Citizen. (n.d.). https://www.city2gether.fr/

CityJSON. (n.d.). CityJSON. https://www.cityjson.org/

Edler, D., Keil, J., & Dickmann, F. (2020). From Na Pali to Earth—An ‘unreal’engine for modern geodata?. In *Modern approaches to the visualization of landscapes* (pp. 279-291). Springer VS, Wiesbaden.

Edler, D., Keil, J., Wiedenlübbert, T., Sossna, M., Kühne, O., & Dickmann, F. (2019). Immersive VR experience of redeveloped post-industrial sites: The example of “Zeche Holland” in Bochum-Wattenscheid. *KN-Journal of Cartography and Geographic Information*, *69*(4), 267-284.

Fabricius, T. (2021, April 19). CityEngine and ArcGIS Urban: One Love. ArcGIS Blog. https://www.esri.com/arcgis-blog/products/city-engine/3d-gis/cityengine-arcgis-urban-one-love/

Fundamentals of WebXR - Web APIs | MDN. (2022, October 28). https://developer.mozilla.org/en-US/docs/Web/API/WebXR_Device_API/Fundamentals

Glassner, A. S. (Ed.). (1989). *An introduction to ray tracing*. Morgan Kaufmann.

Keil, J., Edler, D., Schmitt, T., & Dickmann, F. (2021). Creating immersive virtual environments based on open geospatial data and game engines. *KN-Journal of Cartography and Geographic Information*, *71*(1), 53-65.

Kersten, T. P., Deggim, S., Tschirschwitz, F., Lindstaedt, M., & Hinrichsen, N. (2018). Segeberg 1600—Eine Stadtrekonstruktion in virtual reality. *KN-Journal of Cartography and Geographic Information*, *68*(4), 183-191.

Lehtola, V. V., Koeva, M., Elberink, S. O., Raposo, P., Virtanen, J. P., Vahdatikhaki, F., & Borsci, S. (2022). Digital twin of a city: Review of technology serving city needs. *International Journal of Applied Earth Observation and Geoinformation*, 102915.

Liang, Z., Zhou, K., & Gao, K. (2019). Development of virtual reality serious game for underground rock-related hazards safety training. *IEEE access*, *7*, 118639-118649.

Mat, R. C., Shariff, A. R. M., Zulkifli, A. N., Rahim, M. S. M., & Mahayudin, M. H. (2014, June). Using game engine for 3D terrain visualisation of GIS data: A review. In *IOP Conference Series: Earth and Environmental Science* (Vol. 20, No. 1, p. 012037). IOP Publishing.

Mooney, C. Z. (1997). *Monte carlo simulation* (No. 116). Sage.

Natural light is fundamentally different than artificial light. (2017, September 22). SunlightInside. https://www.sunlightinside.com/light-and-health/natural-light-is-fundamentally-different-than-artificial-light/

Radiance — Radsite. (n.d.). https://www.radiance-online.org/

Scorpio, M., Laffi, R., Masullo, M., Ciampi, G., Rosato, A., Maffei, L., & Sibilio, S. (2020). Virtual reality for smart urban lighting design: Review, applications and opportunities. *Energies*, *13*(15), 3809.

Sen, S., & Khazanovich, L. (2021). Limited application of reflective surfaces can mitigate urban heat pollution. *Nature Communications*, *12*(1), 1-8.

Smart City Technology and IoT Solutions at. (n.d.). AT&T Business. https://www.business.att.com/categories/smart-cities.html

State of the Art in 3D City Modelling. (2022, July 13). GIM International. https://www.gim-international.com/content/article/state-of-the-art-in-3d-city-modelling-2

Steinhage, V., Behley, J., Meisel, S., & Cremers, A. B. (2010, March). Automated updating and maintenance of 3D city models. In *ISPRS joint workshop on" Core Spatial Databases-Updating, Maintenance and Services-from Theory to Practice* (pp. 1-6).

Strategis Groep bv. (n.d.). 3D Cityplanner, the future of urban development, architecture and project development. https://3dcityplanner.com/en/

The Home of Location Technology Innovation and Collaboration | OGC. (n.d.). https://www.ogc.org/

Urban Planning & Design-Smart City Planning | ArcGIS Urban. (n.d.). Esri. https://www.esri.com/en-us/arcgis/products/arcgis-urban/overview

VanDerHorn, E., & Mahadevan, S. (2021). Digital Twin: Generalization, characterization and implementation. *Decision Support Systems*, *145*, 113524.

Wang, Z. H. (2014). Monte Carlo simulations of radiative heat exchange in a street canyon with trees. *Solar Energy*, *110*, 704-713.

Wikipedia contributors. (2022, September 22). Passive solar building design. Wikipedia. https://en.wikipedia.org/wiki/Passive_solar_building_design

Wolf, M., Söbke, H., & Wehking, F. (2020). Mixed reality media-enabled public participation in urban planning. *Augmented Reality and Virtual Reality*, 125-138.

Wright, L., & Davidson, S. (2020). How to tell the difference between a model and a digital twin. *Advanced Modeling and Simulation in Engineering Sciences*, *7*(1), 1-13.

Zender, R., Knoth, A. H., Fischer, M. H., & Lucke, U. (2019). Potentials of virtual reality as an instrument for research and education. *i-com*, *18*(1), 3-15.

Zhao, Y., van den Berg, P. E., Ossokina, I. V., & Arentze, T. A. (2022). Comparing self-navigation and video mode in a choice experiment to measure public space preferences. *Computers, Environment and Urban Systems*, *95*, 101828.