MICROCLIMATE ANALYSIS OF THE TU DELFT CAMPUS

Group 2

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ABSTRACT: With the Urban Heat Island Effect on the rise and 66% of the global population expected to live in the cities by 2050, new ways of building for this urban growth need to be researched. In this report the cooling effects of green and water structures on urban landscapes are examined. To realize this, we opted to recreate a 3D model of the chosen research area based on different datasets. This can then be used in the simulation software ENVI-met to calculate the effect that these structures have on the microclimate. Firstly, we successfully made a 2D inventory based on the different components necessary to run the simulation. Secondly, when converting from the 2D data to 3D data, errors occurred as regards to the tree and building datasets. Thirdly, the simulation failed due to a lack of interoperability between the datasets and softwares. Therefore, we are unable to answer the research question. However, after an in-depth assessment of the FAIRness of data, we conclude that by testing, failing and improving the interoperability of datasets and softwares, we can change our perception of the data we collect and find new ways to store and visualize them.

KEY WORDS: TU Delft, campus, university, microclimate, ENVI-met, sustainability, climate change, Urban Heat Island Effect

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1. INTRODUCTION

Several studies (Yang et al, 2016; Mirzaei, 2015; Gunawardena et al, 2017) have looked at the effect of the Urban Heat Island effect (UHIE), which is widely recognized as a heat accumulation phenomenon. The heat accumulation can be seen as the most discernible effect caused by human activities. Research carried out by the United Nation (2014) indicated that there is an upward trend with 66% of the global population expected to live in cities by 2050, these cities will develop either vertically or horizontally, resulting in a growing amount of heat accumulation (Mirzaei, 2015). This led to a climate change showing increasing frequency and severity of extreme weather events, such as heat waves, wildfires, etc. These events, coupled with the UHIE are likely to amplify the challenges we are facing in this urban growth (PCC, 2014).

With this in mind, the main research question in this paper is: *"To what extent can green and water structures cool urban landscapes?"* We want to know how this applies to our own campus, because we, as students of the Delft University of Technology, have more chances of acquiring the right datasets for this research through our own university. Also, all the components to run the simulation (concretion, buildings, water and green structures) are present. Therefore, the chosen case is the city of Delft in the Netherlands, with a focus on the Campus of the Delft University of Technology. To determine the cooling effect of green and water structures, there are two relevant research strategies for us: 1) collecting existing retrieved and researched data or 2) collecting existing retrieved data to put in a simulation to make our own research project and microclimate calculations. We decided to choose the latter, since this will ensure the need of a digital twin, which is especially interesting in the context of the minor *Spatial Computing for Digital Twinning*. To provide an answer to the formulated research question, we will first need to determine the green and water structures in Delft. Secondly, we will need to analyze and quantify these structures. Following, we will have to translate the acquired datasets into a 3D model, which can then be used in the simulation to calculate the effect that these structures have on the microclimate of the TU Delft campus. In the final section the results will be discussed and the research question answered.

2. RESEARCH STRATEGY

In this chapter, we will take a closer look at the research strategy. The reason we chose this strategy is based on the use of digital twinning that we want to gain a better understanding of the microclimate through a digital twin and with that the accompanying simulation method.

2.1 Digital Twin of the TU Delft Campus

The main goal of this study is to obtain a better understanding of the effects that green and water structures can have on cities through a digital twin. As the case of this research paper is the TU Delft campus, the retrieved data and results of analysis will be primarily useful for the institution of TU Delft and the municipality of Delft. However, the way of researching can be reproduced in other cities or urban districts.

There are many different steps in this research and in making a digital twin. First of all, we needed to get acquainted with the area. So, we started by collecting the necessary datasets from *Publieke Dienstverlening Op de Kaart (PDOK)* to make the 2D inventory maps for buildings, streets, roads, trees, green and water structures. We processed these datasets in *QGIS* software. Afterwards, it was time to make the 3D model in *Rhinoceros 7*, this is a computer-aided design program (CAD-program). During this process, we also needed to obtain certain information like heights, volumes, etc. and therefore we had to look for some extra datasets for the trees and buildings. For the heights of the 3D trees, we retrieved the datasets of *Cobra GroenInZicht*. We first had to process them in 2D in the *QGIS* software to retrieve the heights from the attribute table. For the buildings, we consulted the *3D BAG* and directly imported them into *Rhinoceros 7*.

Lastly, we acquired the raw weather data from *climate.onebuilding.org*. This will be plugged into the simulation later on. However, to be able to draw any conclusions from the results we might obtain, it is necessary for us to understand the data as well. That is why we also used *Climate Consultant*. This is a software designed to translate raw weather data into clear climatological graphics that are easily comprehensible.

2.2 Research method - Simulation

The research strategy is making a simulation that calculates the microclimate for the TU Delft Campus based on the digital twin. The simulation runs as followed: 1) We order the different compartments like buildings, streets, roads, green and water structures into different layers in *Rhinoceros 7*. 2) We need to use a script to run the simulation through *ENVI-met*, because it is a very complex software that utilizes different components to recreate the real life situation. So, we used the script of the course *BK3TE4 Technology 4 - Construction and Climate Design* in the *Grasshopper* component in Rhinoceros 7. This script is vital to combine the last three components of the simulation, which are LunchBox, Dragonfly and Ladybug. *LunchBox* is a Grasshopper plug-in that explores mathematical shapes, paneling, structures, and workflow (*LunchBox*, 2021). This program has necessary tools to run the script. *Dragonfly* uses abstracted building geometries and brings them together to create district scale energy models. These models can be directly simulated in a number of engines (*Ladybug Tools | Dragonfly*, n.d.). This is the program that will translate the geometries into an .inx file, which ENVI-met can understand in their *'Spaces'* component. *Ladybug* on the other hand is "an environmental analysis plugin for Grasshopper. Ladybug combines geometry in Rhinoceros 7 and the parametric interface of Grasshopper with open-source weather data (.epw files) to create site specific climate analysis graphics and diagrams" (*Ladybug+Honeybee for Grasshopper « Baker Lighting Lab*, n.d.). In other words this is the software that will simulate the raw weather data into a digital atmosphere specific to the georeferenced geometries of buildings. 3) If we succeed in making a correct digital twin and importing all the necessary data models into the simulation, step 3 would be to analyze the results. To effectively measure the cooling effect of green and water structures two simulations should be run (Tsoka et al., 2018; Liu et al., 2021). One with green and water structures, and the second one without. In addition, the explanation of the results should be done based on the comparison of the mathematical calculations and previous analysis like the Climate Consultant diagrams, which should allow us to explain any notable outcomes we might obtain.

3. RESEARCH

In this chapter we will describe the actual research to try and answer the main research question of this paper: *"To what extent can green and water structures cool urban landscapes?"* Firstly, we will present the 2D analysis of buildings, streets, roads, trees, greenery and water. Secondly, we will explain the conversion from 2D to a 3D model. Further, we will show the weather diagrams processed by Climate Consultant. Then, we will explain the workings behind the ENVI-met simulation software. Lastly, we will run the simulation and discuss the results.

3.1 2D Inventory of the research area

The script of the course *BK3TE4 Technology 4 - Construction and Climate Design* categorizes the research area into four subcategories: buildings, concretion, greenery, and water bodies into surfaces and solids. The campus is quite scattered, so we decided to limit the research area [Appendix A]. Based on the selected attributes in the datasets of *Basisregistratie Grootschalige Topografie* (BGT) and *Basisregistratie Adressen en Gebouwen* (BAG) that were relevant for our research, we made our own figures [Appendix A]. These subcategories serve as input for the ENVI-met model.

The data we used for the 2D inventory is derived from the dataset BGT and BAG. The information contained in these datasets is loaded into QGIS. Users may explore and visualize spatial relationships with, within, and among spatially explicit datasets using this virtual interface. The datasets BGT and BAG are published on the website (*Datasets - PDOK*, n.d.). The dataset BGT is a detailed large-scale (digital map) of the entire Netherlands, (*Introductie - PDOK*, n.d.). It contains the location of all physical objects such as:

- Buildings
- Roads
- Water
- Railway
- (Agricultural) land

The comprehensive BAG consists of three parts: BAG-panden, a subsection of BAG-panden and the accommodations located there. Location and number designation are also included (Kadaster, n.d.).

PDOK contains a platform holding geodata sets of Dutch Government agencies. The services of Publieke Dienstverlening Op de Kaart comply with national and international standards, including the European INSPIRE standard and the Dutch e-governmental standards. The information about the research area in this case plays an essential role in analyzing and visualizing a social issue like the Urban Heat Island effect (*Over PDOK - PDOK*, n.d.).

The subcategories (as mentioned earlier) can also be divided into different datasets. To determine the location of the water bodies and surfaces in the research area we used the dataset bgt_waterdeel [Appendix A, Figure 1], which includes everything we need for further processing. The greenery was determined by using bgt_begroeid-terreindeel, bgt_ondersteunendwaterdeel and the dataset bgt_vegatatieobject. This includes all of the vegetation our 3D model needs. Initially, the trees were derived from the bgt_vegatieobject [Appendix A, Figure 2]. This dataset did not include the heights and sizes of tree crowns, which were needed to calculate e.g. the effect of shadows on the Urban Heat Island effect on the TU Delft Campus [Appendix A, Figure 3]. They gave us permission to access their dataset, which allowed us to do our computations in ENVI-met.

Determining the concretion [Appendix A, Figure 4] is done by using the datasets bgt_wegdeel, bgt_ondersteunendwegdeel, bgt_weginrichtingslement and bgt_onbegroeidterreindeel. The last datasets contained redundant data, therefore we filtered it, which results in four attributes: verharding_erf, gesloten_verharding, half_verharding, and open_verharding. For the buildings in the research area we used the Basisregistratie Adressen en Gebouwen (BAG), resulting in the attributes pand, pand_deelgebouw and extra_bouwwerk (Kadaster, n.d.). These attributes are merged into 'buildings' [Appendix A, Figure 5]. The 2D maps serve as the inventory for further processing of the information derived from the datasets.

3.2 3D spatial model

The 3D spatial model is based on the obtained data from the datasets of 3DBAG and the ones used for 2D inventory. The 3D model [Figure 6] serves as input for the ENVI-met simulation.

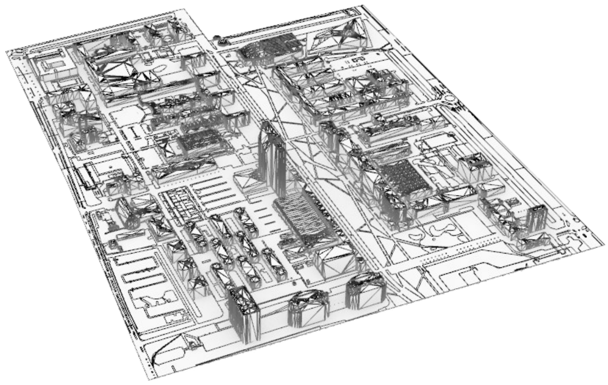

Figure 6, *3D Spatial Model of the TU Delft Campus in Rhinoceros 7. Based on the dataset Basisregistratie Grootschalige Topografie (BGT), Basisregistratie Adressen en Gebouwen (BAG) both derived from PDOK and the 3DBAG dataset.* [Own illustration] (2022). Department of Architecture, Delft University of Technology.

The collection of 3D building models of the Netherlands is called the 3D BAG. It is an open data source. The building information from the Basisregistratie Adressen en Gebouwen (BAG) and the height information from the Actueel Hoogtebestand Nederland (AHN), Basisregistratie Grootschalige Topografie (BGT) and TOP10NL were combined to create the 3D models, which are presented in the dataset at various levels of detail. The 3D BAG is kept up-to-date, so the most recent building stock and elevation data are presented. 3D-BAG is publicly accessible and can be viewed and downloaded by everyone (3D geoinformation research group, n.d.).

The elevation dataset for the Netherlands is the National Height Model of the Netherlands (AHN). The latest version is gathered using airborne laser scanning (LiDAR), with an average point density of eight points per square meter. The third version of AHN, which is gathered in phases between 2014 and 2019, is utilized for the 3D BAG (3D geoinformation research group, n.d.-a).

Roads, canals, and railroads are just a few of the numerous items that make up BGT's comprehensive coverage of the country. The BGT is used for the 3D BAG to identify buildings that overlap with other objects like roads and other structures. Such overlapping structures are identified and eliminated from the reconstruction process (3D geoinformation research group, n.d.-a).

The Topographic Register of the Netherlands includes the TOP10NL in its TOPNL datasets. It simulates a variety of item kinds, including buildings and their purpose. Base maps in visualizations can also be created using the TOP10NL data as a data source. To distinguish different buildings from other BAG items, 3D BAG exclusively uses the buildings from the TOP10NL. These buildings are only models with a simplified shape (3D geoinformation research group, n.d.-a).

The 3D BAG dataset is presented in three levels of detail (LoD). These LoD's are ranked from least details to most details as follows: LoD 1.2, LoD 1.3 and LoD 2.2 [Figure 7]. When inserted into Rhinoceros the datasets are converted into surfaces. The higher the level detail, the more surfaces are needed to recreate the shape of the building (3D geoinformation research group, n.d.-a).

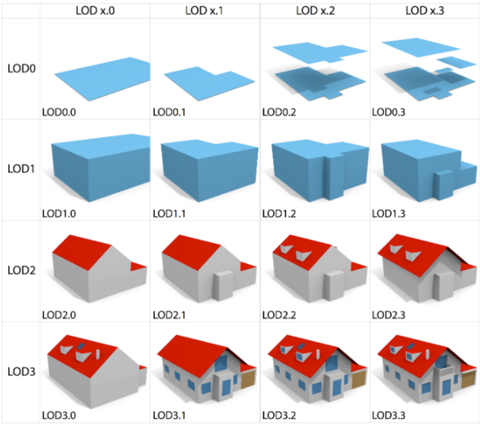

Figure 7, An improved LOD specification for 3D building models
Derived from Biljecki, F., Ledoux, H & Stoter, J. (2016). An improved LOD specification for 3D building models. *Computers, Environment and Urban Systems, 59*, 25-37.

The 3D BAG data was derived from four different tiles, which together show the buildings in the research area. After downloading the tiles with a LoD of 2.2, we inserted them into Rhinoceros 7. The first problem arose afterwards, when the program indicated that there were a lot of open meshes. After joining all the meshes, it still showed that not all of them were closed. The meshes should be closed in order to make solids out of them, which is necessary to run the ENVI-met simulation. To solve this problem we tried to run a self-made Grasshopper script [Figure 8], which allowed us to turn a mesh into a Boundary Representation Model (BREP).

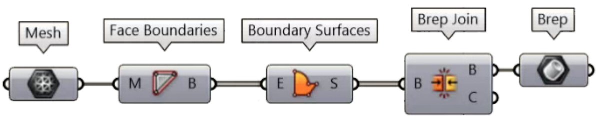

Figure 8, *Grasshopper script.* [Own script] (2022). Department of Architecture, Delft University of Technology.

A mesh compromises vertices, lines, and polygons. BREP, on the other hand, consists of vertices, lines and faces, but these can be curved and the faces operate as surfaces rather than 2D polygons. Thus, after making this translation from meshes to BREPs, the closed meshes became solids, but the open meshes formed open polysurfaces. A solid can not have any interior boundaries or they should have an infinite number (i.e. a solid has an infinite number of inner boundaries, when a cove is created in the shape). The borders of a solid can interact with one another, but only under particular conditions, according to the ISO19107 requirements. The 2D statements had to be generalized for the validity of a 2D polygon because there were no implementation specifications for the 2D primitives. The only adjustments required are that, in 3D, rings become shells, holes become cavities and polygons become solids, some of them are valid and some of them are invalid [Appendix B, Figure 9]. A solid is invalid when the boundaries are not able to interact with each other, so the edges must be closed. If the solid contains a hole and the surfaces are not closed, it will turn out invalid. By contrast, if a gap is filled with surfaces it will turn out valid [Appendix B, Figure 10].

LoD 2.2 did not work in the end. An explanation for this could be that since it is the highest LoD, the chance of invalid solids increases, because more surfaces are needed as explained earlier. To solve this, we used a mix of LoD2.2 and LoD1.2 [Figure 11]. After running the Grasshopper script, the meshes in this level of detail were mostly translated into solids.

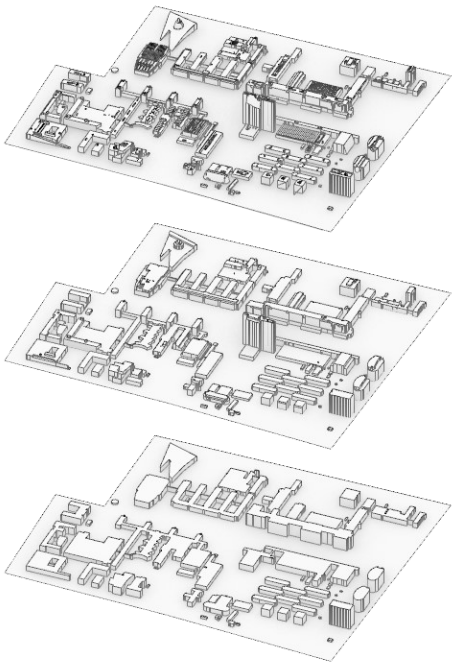

Figure 11, Tested LoDs 1.2, 1.3, and 2.2 on the 3D model of the TU Delft Campus *in Rhinoceros 7* (the model above shows a LoD of 2.2), based on *the dataset Basisregistratie Grootschalige Topografie (BGT), Basisregistratie Adressen en Gebouwen (BAG) both derived from PDOK and the 3DBAG dataset.* [Own illustration] (2022). Department of Architecture, Delft University of Technology.

The difference between 2D GIS and 3D GIS is that points, lines, and polygons [Figure 12] can be used in 2D GIS to display an object's geometry. To enable an interoperable data flow these primitives specify a set of guidelines. The geometric primitives and their guidelines must be expanded to the third dimension in 3D GIS in order to meaningfully define how they interact. Since we regard the constructing models as solids during the process, the SOLID primitive is the most pertinent for the 3D BAG data. This difference is crucial because solids are subject to distinct (stricter) restrictions than other 3D primitives (3D geoinformation research group, n.d.-a).

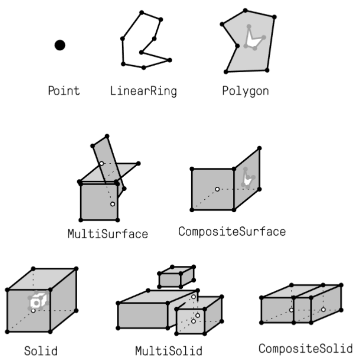

Figure 12, 3D primitives handled by Val3dity
Derived from Ledoux, H. (2018). Val3dity: validation of 3D GIS primitives according to the international standards. *Open Geospatial Data, Software and Standards, 3*, 1.

The data must have a proper geometry in order to be used in multiple applications. When working with data, standards assist to develop a uniform set of rules that both data producers and consumers can follow. Software called Val3dity verifies 3D primitives in accordance with ISO19107 (a global standard). Val3dity is integrated into the workflow of 3D BAG, where the buildings are individually checked. The 3D geoinformation research group (n.d.-b) therefore states that they are unable to identify mistakes in the interaction between different models, see error codes above 500 [Appendix B, Figure 13].

During the translation of the 2D tree dataset of Cobra GroenInZicht (on tree heights and the size of crowns) to the 3D model, a second problem arose. The dataset contains all the elements to translate it into 3D, the given location, and also the size and height of the tree. We were not able to create the 3D trees due to a lack of volumes, which are needed to create trees. Figure 14 is an example of how the trees must look in ENVI-met to perform the simulation. For this reason, we could not implement the tree datasets into the 3D model.

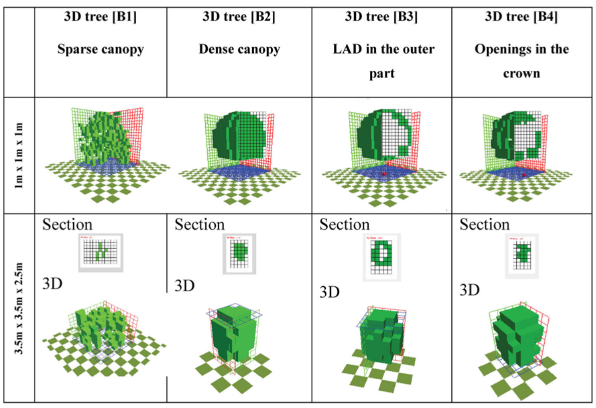

Figure 14, Tree topology B1, B2, B3 and B4 in different resolutions: 1m × 1m × 1m and 3.5m × 3.5m × 2.5m. Derived from Shinzato, P., Simon, H., Duart, D.H.S & Bruse, M. (2019). Calibration process and parametrization of tropical plants using ENVI-met V4 - Sao Paulo case study. Architectural Science Review, 62:2, 112-125.

3.3 Weather data graphics

The graphics are based on the raw weather data from *climate.onebuilding.org*. Climate Consultant has translated the raw weather data into meaningful graphics that we can understand and analyze. As an example, we will discuss one graphic to give an idea on how to read them. Figure 15 shows the Temperature Range graphic. The colors in the legend explain how we should interpret the numbers. For the month of January it says that the mean is about 4℃. The average high and low temperatures range between 2 and 6℃ (yellow). The dots are the lowest -6℃ and highest 12℃ recorded temperatures in the month of January. The green part that goes from the yellow to the extremes (the dots), indicate the fluctuation range that your building should be able to endure. This part is negligible since we are looking at the microclimate of the research area and not at the design of a building. Lastly, the gray part indicates the comfort zone for humans. In Appendix C you can find the other graphics that we looked at to obtain a better understanding about the climate. These graphics are in the same way readable as the example below.

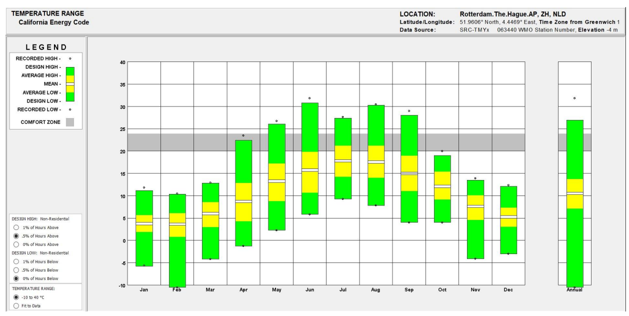

Figure 15, *Temperature Range Graphic. Created by Climate Consultant. Weather data source https://climate.onebuilding.org/sources/default.html.*

3.4 ENVI-met model overview

ENVI-met is a holistic 3D simulation software of surface-plant-air interactions (*intro: modelconcept [A holistic microclimate model]*, n.d.). Holistic means that systems should be seen and treated as wholes. They are only comprehensible and explicable due to their interconnection (Wikipedia contributors, 2022). "It is designed for microscale with a typical horizontal resolution from 0,5 to 10m and a typical time frame of 24h to 48h with a time step of 1 to 5 seconds" (*intro: modelconcept [A holistic microclimate model]*, n.d.). To understand what this means, we will explain the following terms in order: horizontal resolution, time frame and time step and place them in a scale to understand what makes these values 'typical'.

"Horizontal resolution refers to how close two reflecting points can be situated horizontally, and yet be recognized as two separate points rather than one" (*Vertical Resolution Horizontal Resolution Fresnel Zone*, n.d.). In another example we can see that a microscale domain of 20km was simulated with a horizontal resolution from 0,1 to 1km, which results in a

16-million-points mesh (Mesoscale microscale coupling, n.d.). As in our case, we have a microscale domain of 900m with simulation running on a horizontal resolution of 0,5 to 10m. This will lead to a more detailed mesh point. “Time steps slice your input data for analysis into steps defined by three parameters (time step intervals, time step repeat interval and time step reference). When you apply time steps, analysis is completed on each time step independent of data outside of the time step of interest” (*How time stepping works - ArcGIS Pro | Documentation*, n.d.). In ENVI-met the time intervals are set to 1 to 5 seconds. Usually a time frame of 24h or 48h is used, but if the computer engine is powerful enough the software could calculate for a whole month or year (*intro:modelconcept [A holistic microclimate model]*, n.d.). Keep in mind that the bigger the time frame, the longer it takes to calculate.

3.5 Simulation

After finishing the 3D model in Rhinoceros 7 to the best of our capacity, it was time to run the script from *BK3TE4 Technology 4 - Construction and Climate Design* [Figure 21]. As explained earlier, this script is necessary to combine different components that come together in ENVI-met to make a holistic simulated microclimate analysis of the TU Delft Campus (given the accessibility and quality of the used data).

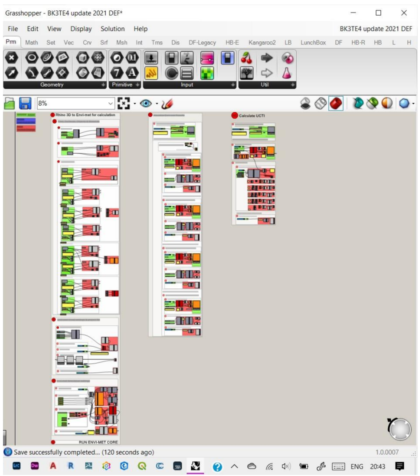

Figure 21, *Grasshopper script*
Derived from Verkuijlen, S.H.(2021). BK3TE4 update 2021 DEF. BK3TE4: Technologie 4 Constructie en Klimaatontwerp.

The simulation process is best explained following the steps of the script. Therefore, we will take you through every step, and we will color the steps in orange or red where different errors occurred. Orange means the data is good but there is a problem obstructing the command from working. Red means there is a lack of data or the wrong data has been set as input.

1. Rhino 3D to ENVI-met for calculation
   - 1.1. Files, Surfaces, Objects & Materials
     - 1.1.1. File & Folders: this is where you name the files that will be created and dedicate them to a folder.
     - 1.1.2. Location & North direction: here we put in the latitude 52.00 and longitude 4.37 of the TU Delft Campus. The North is determined by drawing the north arrow on the designated location.
     - 1.1.3. Material settings: here we have the option to assign a material to each different layer. In short, we chose:
       - Soil - Sand
       - Water - Water
       - Road - Asphalt
       - Street - Concrete
       - Wall - Passive Wall Good Insulation
       - Roof - Passive Wall Good Insulation

       Error: please provide closed geometries.

       - Greenery - Grass
       - Trees - Tree 20m Distinct Crown Layer

       Error: recursive data stream found, this component depends on itself.

After finishing the pre-settings there were already a few errors, since the buildings had not been recognized as solids and the trees had not been imported into the 3D model as explained earlier. However, it was time to continue with the actual simulation (without trees), where the components would be brought together.

   - 1.2. ENVI-met Voxel settings & project file
     - 1.2.1. Voxel & Grid Dimensions: here the voxel and grid dimensions were set to 5 x 5 x 25 [Figure 10].
     - 1.2.2. View Grid in Rhino
     - 1.2.3. Voxelization
     - 1.2.4. Building preview

       Error 1: recursive data stream found, this component depends on itself

       Error 2: cyclical data stream detected, parameter Result is recursive.

     - 1.2.5. Start ENVI-met Spaces for Check

       Error: Input parameter G failed to collect data.

When a data stream is recursive, it means that the operation is not possible because the input data comes in and out as output data (Reilly, 2017). The reason this happened is, because the buildings are not solids, so the program was unable to identify them properly, making the input data 'empty' and thus creating the same 'empty' output data. Another example is the trees, because there were not any trees for the program to identify as trees, thus making the tree component recursive. So, after the 'Building Preview' error, we knew the simulation would not work, due to the lack of interoperability of the datasets and softwares. The 'Start ENVI-met Spaces for Check' error confirmed this assumption, since it clearly states that it was not able to collect the necessary data to make an .inx file that is mandatory for ENVI-met to recreate the environment in its 'Spaces'component. Step 1.3 in the simulation would have been the ENVI-met Simulation Settings. This includes importing the raw weather data, choosing the date and hours to calculate and the EPW wind and terrain roughness. This data would have created a .simx file, which would then be run in ENVI-met Core. After running the ENVI-met files and finishing some personalized preview settings in the script, the calculations could have been made.

As a result, it was not possible to run the simulation due to a lack of interoperability of the datasets and the softwares. The main issues being the missing tree data from Cobra GroenInZicht that was lost in the 2D to 3D conversion and the format of the buildings from the 3D BAG, which the program was unable to identify as solids, and thus as buildings. Another explanation for the building's error, besides the buildings being unsolid, could be due to the way the Voxelization & Grid part was coded. It is possible that if the buildings do not snap onto the grid, it could cause an error in the identification process. From previous experience with ENVI-met we know this was the case in the restricted DEMO version, so although we did not expect this to be an issue in the Pro version, it could partake in the problem or the way the code was written, which assumes to be written for the DEMO version. However, this would still be an issue of interoperability between the script, dataset and software. In short, we are unable to formulate an answer to our research question, since the simulation failed.

4. DATA

In this chapter, we will discuss the FAIRness of all the datasets and softwares that were used during this research. We will start by defining what FAIR means. Then we will discuss FAIRness assessment of each dataset and software individually. Afterwards, we will reflect on how to improve the FAIRness of data. Lastly, we will suggest ways to make our own data as FAIR as possible.

4.1 Data FAIRness

First of all, we need to define what *FAIR data* means. The FAIRness of data can be evaluated based on how findable the data is, how accessible, how interoperable and reusable it is (Wilkinson et al., 2016). Each criteria has subcategories to specify what we understand under each term [Figure 22]. Now that we know which factors make FAIRness, we can describe the FAIR process of data collection.

Box 2 | The FAIR Guiding Principles

To be Findable:
F1. (meta)data are assigned a globally unique and persistent identifier
F2. data are described with rich metadata (defined by R1 below)
F3. metadata clearly and explicitly include the identifier of the data it describes
F4. (meta)data are registered or indexed in a searchable resource

To be Accessible:
A1. (meta)data are retrievable by their identifier using a standardized communications protocol
A1.1 the protocol is open, free, and universally implementable
A1.2 the protocol allows for an authentication and authorization procedure, where necessary
A2. metadata are accessible, even when the data are no longer available

To be Interoperable:
I1. (meta)data use a formal, accessible, shared, and broadly applicable language for knowledge representation.
I2. (meta)data use vocabularies that follow FAIR principles
I3. (meta)data include qualified references to other (meta)data

To be Reusable:
R1. meta(data) are richly described with a plurality of accurate and relevant attributes
R1.1. (meta)data are released with a clear and accessible data usage license
R1.2. (meta)data are associated with detailed provenance
R1.3. (meta)data meet domain-relevant community standards

Figure 22, The FAIR Guiding Principles for scientific data management and stewardship. Wilkinson et al., (2016). Retrieved from https://doi.org/10.1038/sdata.2016.18

We are two third-year bachelor students at the TU Delft in the Minor Spatial Computing for Sustainable Development. This means the university and student status played a key role in obtaining the necessary information and softwares needed for this research.

Firstly, we had to retrieve the datasets to help us inventorize and understand the chosen research area. For the buildings, concretion, trees, water and green structures we made use of *PDOK*. PDOK is an open geodata portal, which is easily findable, accessible to anyone for free, it contains open datasets with a high level of interoperability with multiple softwares, like QGIS and Rhinoceros 7, and thus making the data reusable when allowed by license key. It therefore qualifies as FAIR [Table 1].

Table 1, *FAIRness assessment PDOK datasets.*

	Findable	Accessible	Interoperable	Reusable
PDOK	✅	✅	✅	✅

Since the PDOK tree dataset did not give us enough information to later convert to a 3D model, we had to search for other alternatives. The tree datasets of the *Gemeente Delft* did not contain the trees on campus, so we had to keep looking. Eventually, our professor redirected us to *Cobra GroenInZicht*. Their dataset contained heights as well as tree crowns, which is exactly what we needed for the 3D model. We retrieved their dataset after contacting them. They asked us for which purposes we wanted the data and also gave us two conditions: 1) the research findings may be shared, but we're not allowed to share the raw data 2) we have to share our findings with Cobra GroenInZicht, so they can learn from our research and improve their data. However, as stated earlier this conversion was unsuccessful due to a lack of interoperability, which means there are also no results. This makes the dataset unFAIR [Table 2].

Table 2, *FAIRness assessment Cobra GroenInZicht dataset.*

	Findable	Accessible	Interoperable	Reusable
Cobra GroenInZicht	❌	✅	❌	❌

To model the buildings in 3D, we needed solid shapes of the buildings. We retrieved these from the *3D BAG*, which is an open 3D building data set available to all. It is, therefore, easily findable and accessible. As explained in Chapter 3 the buildings did not were not recognized as solids, making the dataset non-interoperable with the script, and thus non-reusable. For that reason the 3D BAG qualifies as unFAIR [Table 3].

Table 3, *FAIRness assessment 3D BAG dataset.*

	Findable	Accessible	Interoperable	Reusable
3D BAG	✅	✅	❌	❌

For the weather datasets we used the raw data from the open source *climate.onebuilding.org*. From here we retrieved weather datasets from 2007 to 2022 from Weerstation Rotterdam Airport Zestienhoven (*Available Weather Data*, n.d.). This wide range of data will give the simulation engine a better chance of calculating more accurate estimates. Unfortunately, errors in the script occurred before we could get to this part of the simulation, leaving the FAIRness assessment of the dataset in doubt. From previous experience, we know that it would probably work since it was the right .epw file and the right weather data. Still, we can not know for sure, since the simulation failed. Thus, making the data unverified for interoperability and reusability in the simulation. However, the data did work in the Climate Consultant software. Based on these results we conclude that the data is FAIR to the extent we were able to use it [Table 4].

Table 4, *FAIRness assessment climate.onebuilding.org dataset.*

	Findable	Accessible	Interoperable	Reusable
climate.onebuilding.org	✅	✅	✅	✅

To run the simulation we had to use a script that brought together different tools and datasets to create the simulated environment in ENVI-met. We used the Grasshopper script from *BK3TE4 Technology 4 - Construction and Climate Design*, which makes it in itself reusable for us, but inaccessible for others. Even though we had assembled all the data necessary and all the components to make it work, the simulation failed due to a lack of interoperability, as previously explained in Chapter 3.5. The script is therefore unFAIR [Table 5].

Table 5, *FAIRness assessment BK3TE4 Grasshopper script dataset.*

	Findable	Accessible	Interoperable	Reusable
BK3TE4 script	❌	❌	❌	✅

Next, we will move on to the softwares we used in this research, starting with *QGIS*. This is a free and open source geographic information system. Making it easily findable and accessible. Also the PDOK datasets were interoperable, making the data reusable. For this reason, QGIS qualifies as a FAIR software [Table 6].

Table 6, *FAIRness assessment QGIS software.*

	Findable	Accessible	Interoperable	Reusable
QGIS	✅	✅	✅	✅

For the 3D model we used the CAD software called *Rhinoceros 7*. This software demands a license that costs 995€ for commercial purposes or 195€ for students and faculties (Robert McNeel & Associates, n.d.). Thanks to the Delft University of Technology, we as architecture students, got free licenses to use this software, making it accessible to us, but not to others. Rhinoceros 7 was able to understand all the datasets from PDOK and the 3D BAG. The 3D BAG did not translate correctly into solids. The tree dataset from Cobra GroenInZicht was not interoperable at all. Of the six criteria (streets, roads, green, trees, water and buildings) 4 were easily interoperable. One was interoperable but in the wrong format. One was not interoperable. Since this is a standard CAD software, the lack of interoperability probably comes from the datasets. Rhinoceros 7 is overall considered a relatively FAIR software [Table 7].

Table 7, *FAIRness assessment Rhinoceros 7 software.*

	Findable	Accessible	Interoperable	Reusable
Rhinoceros 7	✅	❌	✅	✅

To understand the raw weather data, we made use of Climate Consultant software. This is a free graphic-based computer program to help designers understand their local climate. Since we know this software from our bachelor studies, it is hard to assess the findability of the program. We tried some other Google searches such as 'climate graphic software' and 'weather data graphic software', but Climate Consultant never showed in the top 10 results. Therefore, we assume it to be not easily findable. However, it is a free program accessible to everyone. The weather data was interoperable and the graphics gave good reusable and readable information to interpret the raw weather data. This makes the software relatively FAIR [Table 8].

Table 8, *FAIRness assessment Climate Consultant software.*

	Findable	Accessible	Interoperable	Reusable
Climate Consultant	❌	✅	✅	✅

ENVI-met is the software we used to run the simulation. In Chapter 3.4 we explain more in detail how ENVI-met operates. Firstly, we did some Google searches to assess the findability, since we already knew ENVI-met from previous courses.

Examples of searches are 'microclimate simulation' and 'microclimate software model' where ENVI-met always showed up in the top three searches. This leads us to believe that it is easily findable without prior knowledge of the software. In the context of FAIRness we can say that ENVI-met is not an open source software. It costs 2,900€ for commercial purposes and about 290€ for students (ENVI-met GmbH, 2022). We got a license through a professor from the department of Urbanism, at the Delft University of Technology. Otherwise it would not have been possible to access this software. Since the simulation ultimately failed, it is harder to assess its FAIRness. However, we can confirm that most of the datasets were correctly identified (4 out of 6 due to a lack of interoperability or lack of data), and so interoperable, which means the lack of interoperability probably lies with the datasets and not with the software. Lastly, since the simulation failed it did not give us any output data that could be further reusable. This makes the software unFAIR [Table 9].

Table 9, *FAIRness assessment ENVI-met software.*

	Findable	Accessible	Interoperable	Reusable
ENVI-met	✅	❌	✅	❌

Grasshopper is a component in Rhinoceros 7. It is the program in which the script was written and where the plugins LunchBox, Dragonfly and Ladybug come together to create the simulated microclimate based on the input data. Since it is part of Rhinoceros 7, you would not be able to find it casually and you would also need the Rhinoceros license key to access it. Therefore, we do not consider Grasshopper to be findable and accessible. On the other hand, it is highly interoperable, combining geometries from Rhinoceros with Grasshopper scripts and a variety of plugins. The scripts that are written in Grasshopper are also easily reusable and adaptable to new projects, like we did for the simulation. The software is ultimately unFAIR [Table 10].

Table 10, *FAIRness assessment Grasshopper software.*

	Findable	Accessible	Interoperable	Reusable
ENVI-met	❌	❌	✅	✅

LunchBox is a Grasshopper plugin. If someone would be looking for these specific functionalities within Grasshopper, they would quickly find the LunchBox plugin online. After finding it, you can download it for free. However, it will only work if you have the license key for Rhinoceros and can access Grasshopper. Since it is not universally implementable [A1.1], it is not considered accessible. It is interoperable with Grasshopper and Rhinoceros. The data in this research is not reusable, since the simulation failed [Table 11]. The same goes for the plugins *Dragonfly* and *Ladybug*, except that they are not restricted to Rhinoceros and could be used in different kinds of CAD softwares. Though, you would still have to pay for them, which still makes them inaccessible. For this reason, the three softwares qualify as unFAIR [Table 11].

Table 11, *FAIRness assessment LunchBox software.*

	Findable	Accessible	Interoperable	Reusable
LunchBox	✅	❌	✅	❌
Dragonfly	✅	❌	✅	❌
Ladybug	✅	❌	✅	❌

In conclusion, we were able to obtain all the datasets and softwares we needed to run the simulation. Though, due to a lack of interoperability we were not able to formulate an answer to the research question. Most of the datasets are from open sources, except the tree data [Table 12]. This should not be confused with open source softwares, since the majority of the analysis and simulation softwares were all license key based except for QGIS and Climate Consultant [Table 13]. This research would not have been possible without the connections and help from the university.

Table 12, overview FAIRness assessment datasets.

	Findable	Accessible	Interoperable	Reusable
PDOK	✅	✅	✅	✅
Cobra GroenInZicht	❌	✅	❌	❌
3D BAG	✅	✅	❌	❌
climate.onebuilding.org	✅	✅	✅	✅
BK3TE4 script	❌	❌	❌	✅

Table 13, overview FAIRness assessment softwares.

	Findable	Accessible	Interoperable	Reusable
QGIS	✅	✅	✅	✅
Rhinoceros 7	✅	❌	✅	✅
Climate Consultant	❌	✅	✅	✅
ENVI-met	✅	❌	✅	❌
Grasshopper	❌	❌	✅	✅
LunchBox	✅	❌	✅	❌
Dragonfly	✅	❌	✅	❌
Ladybug	✅	❌	✅	❌

4.2 Improvements on FAIRness

What stands out the most while looking at these tables is the poor level of interoperability in the datasets compartment, and the lack of accessibility in the softwares section. Although, the reusability of the softwares scores fairly low as well, this will not be taken into account, since this was the result of the failed simulation and lack of output data.

The main issues we experienced in this research was the interoperability of the tree dataset from Cobra GroenInZicht and the building dataset from the 3D BAG. The problem with the tree dataset was that the translation from 2D into 3D objects did not work. A solution would be for Cobra GroenInZicht to start a 3D inventory that is compatible with different kinds of CAD and simulation programs. By storing the data in a 3D model, the data is not only clearly visualized but becomes more suitable for use in practice.

The problem with the 3D BAG was the datatype (mesh, solid, polysurface, etc.) of the buildings in which the Rhinoceros translated the dataset. Due to gaps or unconnected borders the buildings were automatically converted into meshes. All attempts to make solids out of them, turned out invalid for this reason. Later on the script could not detect the buildings because of their invalid solid form. In many cases the complexity of the shape of a building makes it increasingly harder to make a solid out of it. That is why we suggest making the buildings into waterproof meshes that have connecting edges. This will prevent errors like the ones we faced to occur, while not having to compromise the level of detail. Another explanation is that the script can only read buildings that snap onto its grid, even though there is no way to test this hypothesis.

In summary, it would be useful to report these findings, so organizations behind these datasets can update them and improve their interoperability. This way they can be more suitable for future research.

4.3 Making our data FAIR

In the context of FAIRness, we would like our paper to be findable, accessible, interoperable and reusable to whomever it might concern. For reusability purposes, we have tried to be as complete and precise as possible in our work, documenting every step of our process. With this in mind, we will upload our work to the repository of the Delft University of Technology, where it will become available online.

5. CONCLUSION

The results of this research are especially useful to the Gemeente Delft and the Delft University of Technology, but can also be beneficial for any city or urban landscape that would like to diminish the negative impact of the Urban Heat Island Effect on their grounds by means of a simulation. In conclusion, we are unable to answer the main research question: *"To what extent can green and water structures cool urban landscapes?"*, since the simulation failed and the chosen strategy did not work.

Firstly, looking back on our research we can state that for the 2D model there were four subcategories (concretion, buildings, water and green structures), and we were able to inventorize them all. Secondly, in the 3D model problems started to occur. Namely, when it came to the tree data from Cobra GroenInZicht and the insertion of the 3D BAG. The main issue with the tree data was that the necessary information, like heights and tree crown sizes, was lost in translation to 3D. This makes the dataset unusable. The problem with the 3D BAG consisted of the wrong datatype of the buildings. These were automatically converted into meshes, and even by decreasing the LoD, it was not possible to make all of them solids. This means that the conversion from 2D to 3D was only half successful. Thirdly, the weather data graphics were successful and allowed us to gain a better understanding of the climate of Delft. Following, as stated earlier the simulation did not work. This is due to the loss of the tree dataset and the lack of interoperability of the 3D BAG in the 3D model. The script showed multiple errors all referring back to the lack of interoperability between the datasets and softwares.

In the context of FAIRness, we were able to obtain all the datasets and softwares we needed to run the simulation. Most of the datasets are from open sources, except the dataset from Cobra GroenInZicht. The majority of the analysis and simulation softwares were all license key based except for QGIS and Climate Consultant. In short, this research would not have been possible without the connections and help from the university. To improve the FAIRness of data, a solution for the tree dataset would be for Cobra GroenInZicht to store the information they currently possess into a 3D inventory that is compatible with different kinds of CAD and simulation programs, as well as making their data more interoperable and reusable. A suggestion for the 3D BAG would be to make the buildings into waterproof meshes that have connecting edges. This way you can have the required LoD and the conversion to solids can be done afterwards following the Grasshopper script.

In short, by testing, failing and improving the interoperability of datasets and softwares, we can change our perception of the data we collect and find new ways to store and visualize them.

6. DISCUSSION

The outcome of this research has given insights into the operations of the simulation software ENVI-met. However, we encountered many limitations during the data collection phase and conducting the preparations needed for the simulation. This chapter provides a discussion on our research process. Potential consequences and limitations are analyzed, as well as their implications concerning the results.

Firstly, we realized that we would not have been able to access most of the softwares used in this research, if we had not been students at the Delft University of Technology. This could be a big limitation for other researchers, organizations or businesses trying to apply the same research method. Secondly, the simulation failed, therefore we were unable to provide an answer to our research question, or have reusable data, which was the main purpose of choosing this research strategy. Looking back now, it would be interesting for future researchers to look into the other suggested strategy: looking into existing retrieved and researched data and see what conclusions can be drawn from that. Maybe this alternative method will provide reusable data.

We ended up exploring in detail the process of data collection, the assessment of data FAIRness and the operations behind multiple kinds of softwares. Despite the fact that the original research question remained unanswered, we believe this research has yielded meaningful results in the field of Open Urban Data Governance, even though we had never previously considered investigating this or encountering so many problems with it. This gives rise to a new research question: *"How can we improve communication between dataset makers and dataset users, so that the level of interoperability corresponds to the purposes of usage?"* This could especially be an interesting consideration in the development of smart cities and digital twins.

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APPENDIX

Appendix A - 2D inventory of the research area

Figure 1, *Waterbodies and surfaces (waterdeel) on the TU Delft Campus based on the dataset Basisregistratie Grootschalige Topografie (BGT), conducted from PDOK.* [Own illustration] (2022). Department of Architecture, Delft University of Technology.

Figure 2, *Greenery and location of trees on TU Delft Campus based on the dataset Basisregistratie Grootschalige Topografie (BGT), conducted from PDOK, and the dataset from Cobra GroenInZicht.* [Own illustration] (2022). Department of Architecture, Delft University of Technology

Figure 3, *Green structures, trees with heights and crown sizes on the TU Delft Campus based on the dataset Basisregistratie Grootschalige Topografie (BGT), conducted from PDOK and the dataset from Cobra GroenInZicht.* [Own illustration] (2022). Department of Architecture, Delft University of Technology.

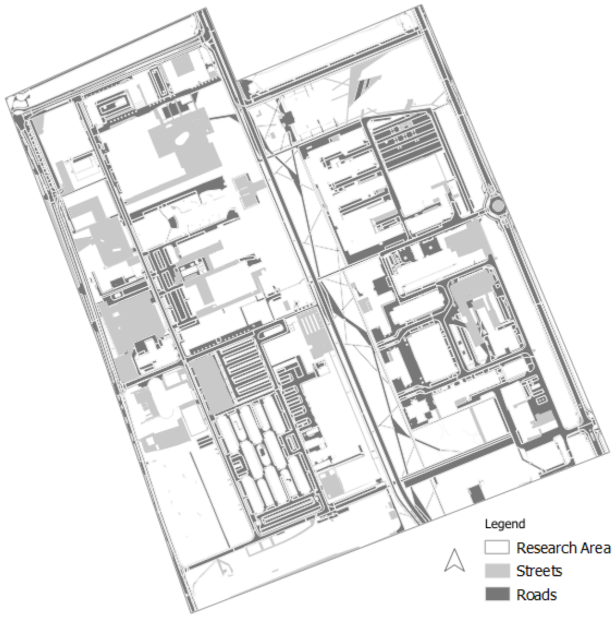

Figure 4, *Concretion (roads and streets) on TU Delft Campus based on the dataset Basisregistratie Grootschalige Topografie (BGT), conducted from PDOK.* [Own illustration] (2022). Department of Architecture, Delft University of Technology.

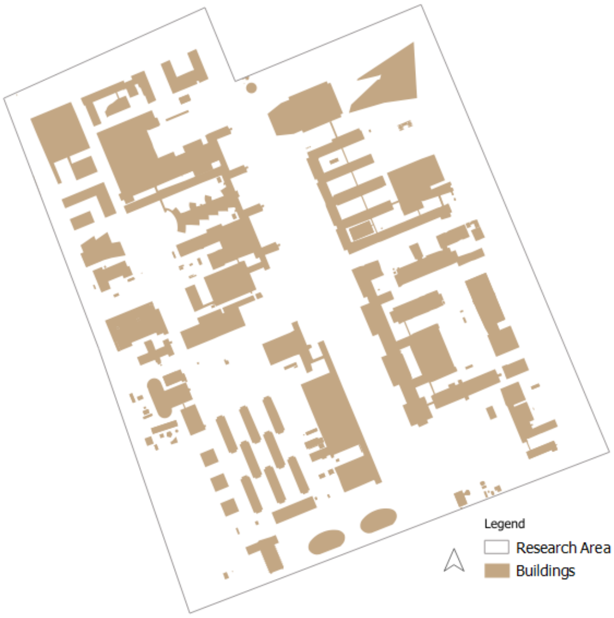

Figure 5, *Buildings (panden, pand-deelgebouw and extra-bouwwerk) on TU Delft Campus based on the dataset Basisregistratie Adressen en Gebouwen (BAG), conducted from PDOK*. [Own illustration] (2022). Department of Architecture, Delft University of Technology.

Appendix B - 3D spatial model

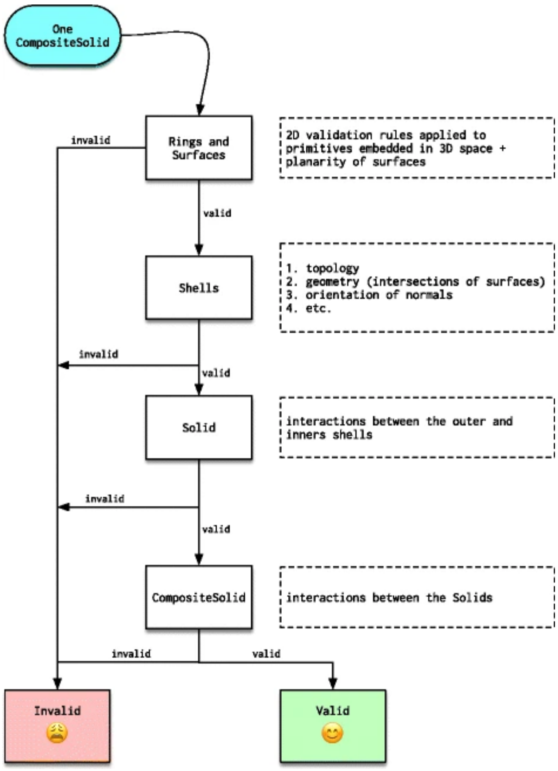

Figure 9, The hierarchical workflow used by Val3dity
Derived from Ledoux, H. (2018). Val3dity: validation of 3D GIS primitives according to the international standards. Open Geospatial Data, Software and Standards, 3, 1

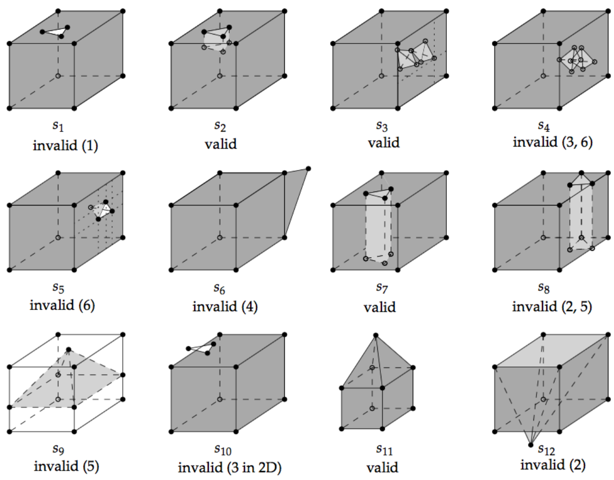

Figure 10, Invalid and valid solids
Derived from Ledoux, H. (2018). Val3dity: validation of 3D GIS primitives according to the international standards. Open Geospatial Data, Software and Standards, 3, 1

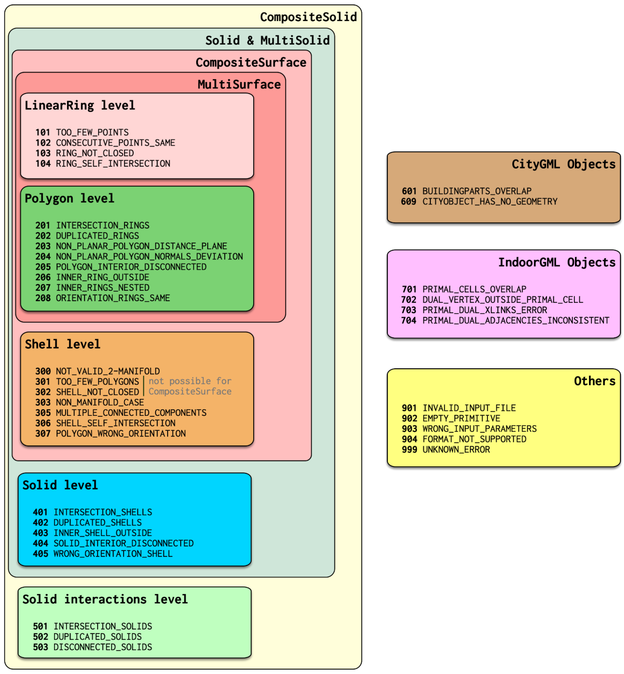

Figure 13, Val3dity error codes
Derived from Errors — val3dity 2.3.1 documentation. (n.d.). Geraadpleegd op 28 oktober 2022, van https://val3dity.readthedocs.io/en/latest/errors/

Appendix C - Weather data graphics

Climate Consultant translates the raw weather data into many different graphics. In this section you can see a manual selection of the graphics that were most meaningful to us and helped us gain an understanding of the climate.

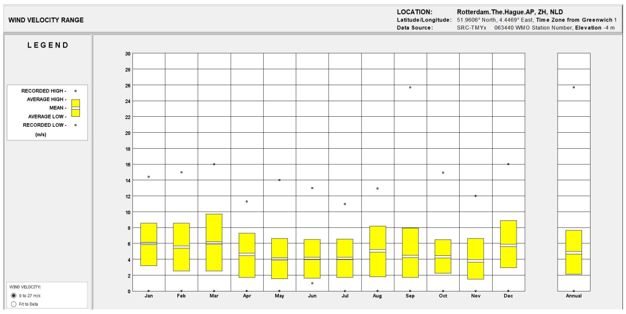

Figure 16, Wind Velocity Range Graphic. Created by Climate Consultant. Weather data source https://climate.onebuilding.org/sources/default.html.

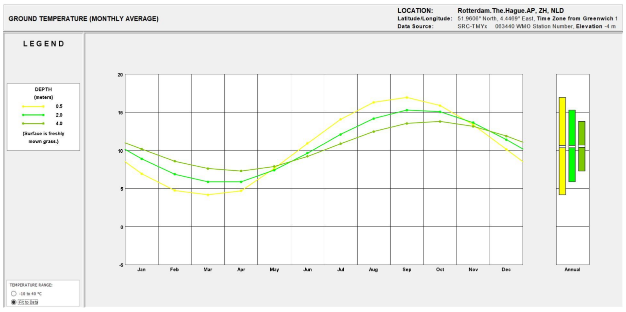

Figure 17, Ground Temperature (monthly) Graphic. Created by Climate Consultant. Weather data source https://climate.onebuilding.org/sources/default.html.

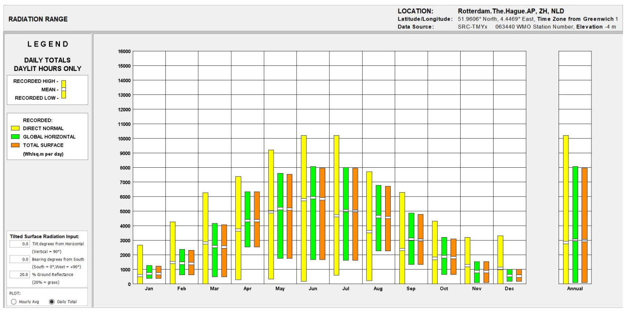

Figure 18, Radiation Range Graphic. Created by Climate Consultant. Weather data source https://climate.onebuilding.org/sources/default.html.

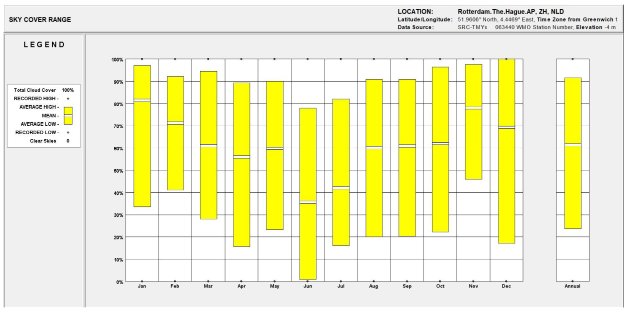

Figure 19, Sky Cover Range Graphic. Created by Climate Consultant. Weather data source https://climate.onebuilding.org/sources/default.html.

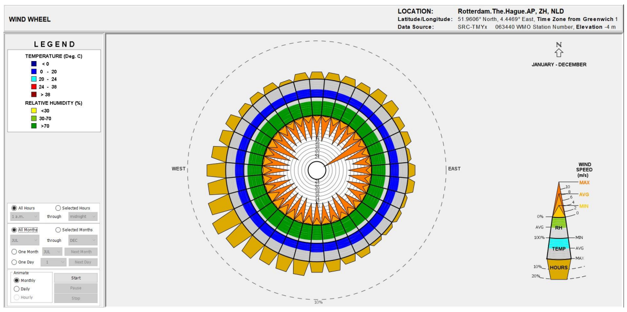

Figure 20, Wind Wheel Graphic. Created by Climate Consultant. Weather data source https://climate.onebuilding.org/sources/default.html.