Building flood resilient cities

Developing a semantic 3D-city flood model for spatial planning support with a Flood Resilience Score

Graduation thesis

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Acknowledgement

When I started the research proposal for my graduation thesis for my double masters a year and a half ago, I knew very little about 3D models, how they are generated and what they can be used for, what digital twins actually entail, or how flood simulation models work. There were several people throughout this process that helped me navigate this new world. I would like to thank my supervisors Pieter Pauwels, Aloys Borgers and especially Giorgio Agugiaro for taking the time to answer all my questions and sometimes nudging me into the right direction when I myself could not see which path I should take next. In addition, I would like to thank Corné Helmons of T3D for his insight into how the industry utilizes semantic 3D city models in regard to flooding.

And finally, a special thanks to my family and friends who always had a listening ear and good advice through the lows of this graduation thesis but also always had time to celebrate the highs. Thanks for always making sure that I had a warm dinner and someone to talk to. There is nothing more important in this world than family and friends and I am so glad to have so many people in my corner that I can always count on!

Lara Andriessen, January 16th, 2023.

Foreword

The first time I was introduced to a CityGML data model was in 2016 for the Bachelor course '*Geografisch modelleren van de gebouwde omgeving*'. Up to that point I had followed my Bachelor Sustainable Innovation and knew nothing about the digitalization within the building industry and was far from understanding what CityGML data models entailed. Only years later when I started my thesis would I discover the interesting world behind that one untitled picture on a lecture slide that I saw that day of a 3D model of a (not too pretty) street. I was dumbstruck. I know that street. I had walked along that street for nearly 20 years of my life. There was the McDonalds I used to go to with the insatiable hunger of a teenager when I had to change busses to go home from my high school; and right next to it was the optician where I bought my first pair of glasses; followed by many other stores which I knew by heart. And on the right side - taking up nearly half of the pavement - those annoying raised beds of greenery that the municipality had put in a few years before to make the street look nicer but which looked dead all year round and only obstructed the walk flow.

Nowadays I'm still shocked. How could the German city where I was born and raised, a city that feels like it's been fighting technological growth and innovation for decades, where I always have to carry cash with me because there is a great chance that I can't pay by card, be one of the first cities in the world that was partially modelled in CityGML? Now I know that the Netherlands and Germany are at the forefront of the world when it comes to the research and application of semantic 3D city models. And that the initiative *Spatial Data Infrastructure North Rhine Westphalia* created the data file that I saw a glimpse of so many years ago. So far though, I have been unable to get my hands on the original data file to ravel in it myself.

For a long time, I have been fascinated by the fact that the built environment shapes people's lives, experiences, and memories. A city can help people express themselves, create a feeling of never being alone, of connectedness, of safety, or provide a silent oasis when needed. At the same time, a poorly designed city – of which there are sadly many - can lead to disconnectedness, chaos, loneliness, vulnerability, and even death. To me, the complexity of a city in mesmerizing and there is beauty in the fact that one person will never fully understand the inner workings and intrinsic web of a city. Even though I try to do so - to a certain extent - with this thesis.

Climate change and the causes and effects of it, are another obsession of mine that has influenced me and my studies throughout my life. So it felt unnatural to me - unthinkable even - to not include climate change in my thesis one way or another. And with my love for the North Sea and the Netherlands, it quickly became clear that I wanted to research the effect that water can have on a city, or rather the nuisance and danger of it in a country that – for a whopping 59% of its land area - is vulnerable to flooding.

As probably everyone who ever graduated will say, the process was far from easy. I remember many lonely days on floor 5 of Vertigo. But this made the days when someone else joined me at the self-proclaimed CME graduation corner - with a lovely view of the buildings atrium - so much easier. Working on my graduation thesis by myself also taught me that I am not made for lonesome work but enjoy working within a team, laughing together and discussing the topic at hand.

Still, I can say that I very much enjoyed my graduation topic and that there was never a day that I wished I had chosen something different. Although a smaller scope would have probably saved me a lot of time and energy…

Thank you for reading my thesis, I hope you enjoy it!

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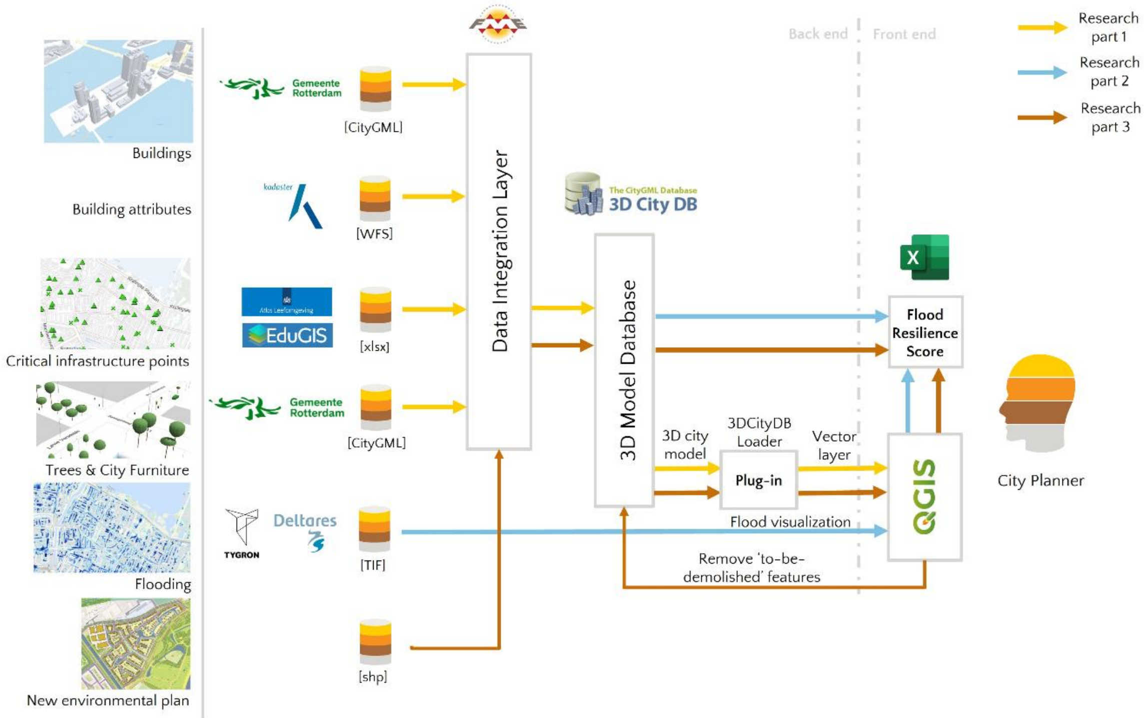
Summary

According to the 2020 Global Risk Report by the World Economic Forum (2020), three of the top five risks that the world is currently facing - by both likelihood and impact - are related to climate. Among extreme weather events, flooding is seen as one of the major contributors to loss of human life and economic damage. The UN environment programme (2020), furthermore, states that floods are going to become more frequent in the near future due to long-term global climate change making floods an even more serious threat. Urban areas are especially vulnerable to floods due to their high population and infrastructure density. At the same time, urbanization is changing the hydrological status of urban areas and the flow path of the water by building new roads and buildings and destroying a city's natural flood defence system such as the water infiltration rate of soil in the process (World Economic Forum, 2019; Yang & Zhang, 2011; Zhi et al, 2020).

Building **flood resilient cities** is therefore becoming increasingly important to mitigate more extreme urban hazards, withstand the increased threats and recover from incidents more quickly.

This research presents a process of developing an open semantic 3D city model based on CityGML that can be connected to the results of a flood simulation model to uncover the direct and indirect effects of future floods on a city, its inhabitants and its critical infrastructure and quantify the effects in a Flood Resilience Score. In addition, this study explores the potential of using the developed model as a spatial planning support tool for city planners to prioritize the redevelopment of certain areas and to test new spatial design decisions. Below, the system architecture of the developed spatial planning support tool that is at its core an open semantic 3D city flood model, is depicted. Throughout the study, there were different ways of modelling certain parts of the process, may it be the choice of base model or the use of certain software. The main argument that influenced these decisions was the leading question; 'would urban planners (with a little help from programmers) be able to use this model themselves?', often resulting in choosing the 'simpler' option.



System architecture

The process developed in this graduation thesis consists of three parts; the development of a semantic 3D city model in combination with the results of a flood simulation model, the development of a Flood Resilience Score, and the development of a spatial planning support tool for urban planners.

The first part (Chapter 4) successfully develops a semantic 3D city flood model of Rotterdam. The process of creating the semantic 3D model begins with setting up the model including obtaining and validating 3D city data from the Municipality of Rotterdam. The CityGML files that store the 3D city building data are then enriched with additional building information and infrastructure points that were identified as playing a critical role during floods (Section 2.1.5). This information is later used in Chapter 5 to evaluate the impact of the flood on buildings and households. Additionally, other fixed built environment objects such as trees, lamp posts and trash bins are added to the model. The process of enriching the 3D city model turned out to be a long one because many of the files had validation and coding errors which first had to be resolved before the files could be imported into the 3DCityDB. To be able to connect two future flood scenarios and their flood inundation maps to the 3D city model, a connection was created between the 3DCityDB containing the 3D city data and QGIS. The flood layers were then imported into QGIS and the two flood scenarios alongside the 3D city model were visualized in QGIS. Overall, this chapter shows that it is indeed possible to develop a data-enriched 3D city model based on CityGML and connect flood simulation output to it which functions as a basis to later on better understand and prepare for the potential impacts of flooding on a city.

Within the second part of the study (Sections 5.1 & 5.2), a Flood Resilience Score is developed. To develop the score, first, a simple spatial analysis is run in QGIS to select all buildings that are flooded followed by a more complex spatial analysis - which also takes the flooded critical infrastructure points and their reach into account - to select all buildings that are also indirectly affected by the flood. The information on these affected buildings is then extracted and merged with additional information from the 3D city model in 3DCityDB which could not be transferred to QGIS. The total numbers of (directly (and indirectly) affected) households/buildings/infrastructure points are then calculated and used as input for the Flood Resilience Score. Following the development of the score, the results for the total study area are used as a baseline to compare and evaluate the Flood Resilience Scores of the different neighbourhoods. This comparison highlights certain neighbourhoods in the study area that require the attention of urban planners.

During part 3 (Sections 5.3 & 5.4) the potential of developing a spatial planning support tool for city planners based on the developed semantic 3D city flood model is explored. To change the 3D model in such a way that future environmental plans can be included when calculating the resilience of the study area includes several steps. First, the urban planner has to create a geo-referenced Shapefile including the ground area of each building, the height at which the building will be constructed using the local AHN, and embed a unique identifier into each building that can later be used as a primary key. In this case, the existing spatial plans for the large-scale urban development of 'Nieuw Kralingen' in the city of Rotterdam are utilized. Next, the 2D Shapefile is transformed into a 3D CityGML file and enriched with data using FME. After removing the buildings and fixed objects that would be demolished, the new 3D spatial plan is imported into the existing semantic 3D city model, the same spatial analyses are run as in Section 5.1 and the Flood Resilience Scores for the new environmental plan are calculated. At the end of the study, the results of the scores for Nieuw Kralingen are evaluated and compared to the scores of the total study area and it is concluded that, overall, Nieuw Kralingen is less affected by a flood than the total study area.

This study offers a deeper insight into semantic 3D city modelling and tests the limits of CityGML models in combination with openly available data and software. While using Rotterdam as a study area, the research provides both visual and quantified insight into the direct and indirect effects of a flood, allowing for a more comprehensive understanding of the potential impacts. The 3D city flood model and the resulting Flood Resilience Score can also be changed and further enriched based on the data available, allowing for a dynamic and adaptable model that can be updated as new information becomes available.

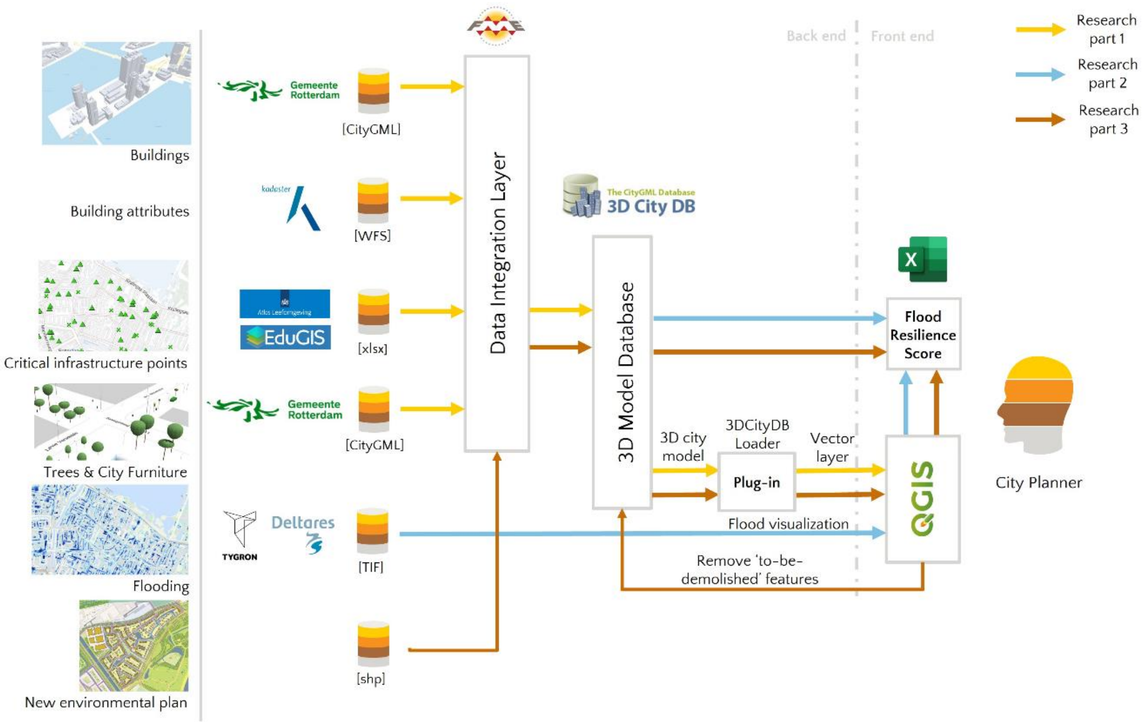
Overall, this research is a first step towards the process automation of developing these models, which has the potential to greatly improve our ability to understand, prepare, and build for floods and to make 3D-model-based spatial planning support tools more accessible and useful for urban planners.

Nederlandse samenvatting

Volgens het Global Risk Report 2020 van het World Economic Forum (2020) houden drie van de vijf grootste risico's waarmee de wereld momenteel wordt geconfronteerd - zowel qua waarschijnlijkheid als qua gevolgen - verband met het klimaat. Wat extreme weersomstandigheden betreft, worden overstromingen beschouwd als een van de belangrijkste oorzaken van verlies aan mensenlevens en economische schade. Het VN-Milieuprogramma (2020) stelt voorts dat overstromingen in de nabije toekomst vaker zullen voorkomen als gevolg van de wereldwijde klimaatverandering op lange termijn, waardoor overstromingen een nog ernstigere bedreiging vormen. Stedelijke gebieden zijn bijzonder kwetsbaar voor overstromingen vanwege de hoge bevolkings- en infrastructuurdichtheid. Tegelijkertijd verandert verstedelijking de hydrologische status van deze gebieden en de stroombaan van het water door de aanleg van nieuwe wegen en gebouwen en vernietigt zo het natuurlijke waterkeringssysteem van een stad, zoals de waterinfiltratiesnelheid van de bodem in het proces (World Economic Forum, 2019; Yang & Zhang, 2011; Zhi et al, 2020).

Het bouwen van overstromingsbestendige steden wordt daarom steeds belangrijker om extremere stedelijke gevaren te beperken, de toegenomen bedreigingen te weerstaan en sneller te herstellen van incidenten.

Dit onderzoek presenteert een proces voor de ontwikkeling van een open semantisch 3D-stadsmodel op basis van CityGML dat kan worden gekoppeld aan de resultaten van een overstromingssimulatiemodel om de directe en indirecte effecten van toekomstige overstromingen op een stad, haar inwoners en haar kritieke infrastructuur bloot te leggen en de effecten te kwantificeren in een overstromingsbestendigheidsscore (Flood Resilience Score). Bovendien onderzoekt deze studie de mogelijkheden om het ontwikkelde model te gebruiken als een instrument ter ondersteuning van de ruimtelijke ordening voor stadsplanners om de herontwikkeling van bepaalde gebieden te prioriteren en nieuwe ruimtelijke ontwerpbeslissingen te testen. Hieronder wordt de systeemarchitectuur weergegeven van het ontwikkelde 'tool' ter ondersteuning van de ruimtelijke ordening, dat in de kern een open semantisch 3D-stadsoverstromingsmodel is. Tijdens het onderzoek waren er verschillende manieren om bepaalde onderdelen van het proces te modelleren, of het nu ging om de keuze van het basismodel of het gebruik van bepaalde software. Het belangrijkste argument dat deze beslissingen beïnvloedde was de leidende vraag: "zouden stedenbouwkundigen (met een beetje hulp van programmeurs) dit model zelf kunnen gebruiken?", waardoor vaak voor de "eenvoudigere" optie werd gekozen.



Systeemarchitectuur

Het in deze afstudeerscriptie ontwikkelde proces bestaat uit drie delen; de ontwikkeling van een semantisch 3D-stadsmodel in combinatie met de resultaten van een overstromingssimulatiemodel, de ontwikkeling van een overstromingsbestendigheidsscore (Flood Resilience Score) en de ontwikkeling van een instrument ter ondersteuning van de ruimtelijke ordening voor stedenbouwkundigen.

Het eerste deel (hoofdstuk 4) ontwikkelt met succes een semantisch 3D-stadsoverstromingsmodel van Rotterdam. Het proces van het creëren van het semantische 3D model begint met het opzetten van het model, inclusief het verkrijgen en valideren van 3D stadsgegevens van de Gemeente Rotterdam. De CityGML-bestanden waarin de 3D-gebouwgegevens zijn opgeslagen, worden vervolgens aangevuld met gebouwinformatie en infrastructuurpunten waarvan is vastgesteld dat ze een kritische rol spelen tijdens overstromingen (paragraaf 2.1.5). Deze informatie wordt later in hoofdstuk 5 gebruikt om de gevolgen van de overstroming voor gebouwen en huishoudens te evalueren. Daarnaast worden andere vaste objecten in de bebouwde omgeving, zoals bomen, lantaarnpalen en vuilnisbakken aan het model toegevoegd. De uitbreiding van het 3D-stadsmodel bleek een langdurige opgave omdat veel van de bestanden validatie- en codeerfouten bevatten die eerst moesten worden opgelost voordat de bestanden in de 3DCityDB konden worden geïmporteerd. Om twee toekomstige overstromingsscenario's en hun overstromingskaarten aan het 3D-stadsmodel te kunnen koppelen, werd een verbinding gemaakt tussen de 3DCityDB met de 3D-stadsgegevens en QGIS. De overstromingslagen werden vervolgens geïmporteerd in QGIS en de twee overstromingsscenario's werden samen met het 3D-stadsmodel gevisualiseerd in QGIS. Over het geheel genomen toont dit hoofdstuk aan dat het inderdaad mogelijk is om een met data verrijkt 3D-stadsmodel te ontwikkelen op basis van CityGML en daaraan een overstromingssimulatie te koppelen die als basis dient om later de potentiële gevolgen van overstromingen voor een stad beter te begrijpen en daarop voorbereid te zijn.

In het tweede deel van de studie (delen 5.1 en 5.2) wordt de overstromingsbestendigheidsscore (Flood Resilience Score) ontwikkeld. Om deze score te ontwikkelen wordt eerst een eenvoudige ruimtelijke analyse in QGIS uitgevoerd om alle gebouwen te selecteren die overstroomd zijn, gevolgd door een meer complexe ruimtelijke analyse - die ook rekening houdt met de overstroomde kritieke infrastructuurpunten en hun bereik - om alle gebouwen te selecteren die ook indirect door de overstroming zijn getroffen. De informatie over deze getroffen gebouwen wordt vervolgens geëxtraheerd en samengevoegd met aanvullende informatie uit het 3D-stadsmodel in 3DCityDB die niet naar QGIS kon worden overgebracht. Het totale aantal (direct en indirect getroffen) huishoudens/gebouwen/infrastructuurpunten wordt vervolgens berekend en gebruikt als input voor de overstromingsbestendigheidsscore (Flood Resilience Score). Na de berekening van de score worden de resultaten voor het totale studiegebied gebruikt als basislijn om de overstromingsbestendigheidsscores (Flood Resilience Score) van de verschillende buurten te vergelijken en te evalueren. Uit deze vergelijking blijkt dat bepaalde buurten in het studiegebied de aandacht van stedenbouwkundigen nodig hebben.

In deel 3 (paragrafen 5.3 & 5.4) worden de mogelijkheden onderzocht om een instrument ter ondersteuning van de ruimtelijke ordening voor stadsplanners te ontwikkelen op basis van het ontwikkelde semantische 3D-stadsoverstromingsmodel. Om het 3D-model zodanig aan te passen dat toekomstige milieuplannen kunnen worden meegenomen bij de berekening van de veerkracht van het studiegebied, moeten verschillende stappen worden doorlopen. Eerst moet de stadsplanner een Shapefile met georeferentie creëren, waarin het grondoppervlak van elk gebouw en de hoogte waarop het gebouw zal worden gebouwd gebruik makend van het lokale AHN, zijn opgenomen, en elk gebouw een unieke identificatiecode geeft die later als primaire sleutel kan worden gebruikt. In dit geval worden de bestaande ruimtelijke plannen voor de grootschalige stedelijke ontwikkeling van "Nieuw Kralingen" in de stad Rotterdam gebruikt. Vervolgens wordt de 2D Shapefile omgezet in een 3D CityGML bestand en aangevuld met gegevens met behulp van FME. Na verwijdering van de gebouwen en vaste objecten die gesloopt zouden worden, wordt het nieuwe 3D ruimtelijke plan geïmporteerd in het bestaande semantische 3D stadsmodel, worden dezelfde ruimtelijke analyses uitgevoerd als in paragraaf 5.1 en worden de Flood Resilience Scores voor het nieuwe omgevingsplan berekend. Aan het eind van de studie worden de resultaten van de scores voor Nieuw Kralingen geëvalueerd en vergeleken met de scores van het totale studiegebied en wordt geconcludeerd dat Nieuw Kralingen over het geheel genomen minder wordt getroffen door een overstroming dan het totale studiegebied.

Deze studie biedt een dieper inzicht in semantische 3D stadsmodellering en test de grenzen van CityGML modellen in combinatie met openlijk beschikbare gegevens en software. Met Rotterdam als studiegebied biedt het onderzoek zowel visueel als gekwantificeerd inzicht in de directe en indirecte effecten van een overstroming, waardoor een vollediger begrip van de potentiële gevolgen mogelijk wordt. Het 3D-stadsoverstromingsmodel en de resulterende Flood Resilience Score kunnen ook gewijzigd en verder uitgebreid worden op basis van beschikbare gegevens, waardoor een dynamisch en aanpasbaar model ontstaat dat kan worden geactualiseerd wanneer nieuwe informatie beschikbaar komt.

Al met al is dit onderzoek een eerste stap naar de automatisering van het ontwikkelingsproces van deze modellen, die ons de mogelijkheid geven om overstromingen te begrijpen, ons hierop voor te bereiden en hiermee te bouwen aanzienlijk kan verbeteren en op 3D-modellen gebaseerde hulpmiddelen voor ruimtelijke ordening toegankelijker en nuttiger kan maken voor stadsplanners.

Abstract

With climate change accelerating, flooding is becoming a major global risk. Urban areas in particular are vulnerable to flooding due to their high population and infrastructure density. At the same time, water-run off is increased because of soil sealing and soil compression. Building flood resilient cities is therefore becoming increasingly important to mitigate floods, withstand the increased threats and recover from these events more quickly while reducing the human and economic cost of floods in the process.

This research presents a process of developing an open semantic 3D city model based on CityGML that can be connected to the results of a flood simulation model to uncover the direct and indirect effects of future floods on a city, its inhabitants and its critical infrastructure and quantify the effects in a Flood Resilience Score. In addition, this study explores the potential of using the developed model as a spatial planning support tool for city planners to prioritize the redevelopment of certain areas and to test new spatial design decisions. The open semantic 3D city flood model of Rotterdam is created by obtaining and validating 3D city data, enriching the CityGML files with additional building and infrastructure information, and connecting the model to flood simulation results. The Flood Resilience Score is then developed by quantifying the direct and indirect impacts of flooding on buildings, households, and critical infrastructure points to evaluate the flood resilience of the neighbourhoods of Rotterdam. Lastly, a spatial planning support tool is developed to evaluate the flood resilience of the new environmental plan 'Nieuw Kralingen' in Rotterdam.

Overall, the process development in this research can help cities better understand the impacts of flooding and change their spatial planning accordingly.

Keywords: Semantic 3D city models, CityGML, 3DCityDB, Flood Resilience Score, spatial planning

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1. Introduction

1.1 Problem definition

With climate change accelerating all over the world and its effects intensifying, the Deltaprogramma Ruimtelijke Adaptatie (2016) has identified four threats to the Netherlands; floods, heavy rainfall, extreme heat, and extreme drought. These threats are only expected to increase in likelihood and intensity in the near future. Reducing climate change and mitigating the effects of these four threats, should therefore be a priority to the people that shape the country. One of the threats that the Netherlands has a long-standing history with, is the excess of water. In particular the excess of water due to coastal floods can have a devastating impact on a country that – for a quarter of its surface - is located below sea level. This long history of dealing with floods has made the Netherlands expert on the topic of flood defence systems. Dealing with the now looming additional threat of more frequent and intense rainfalls that lead to floods, however, is something that the country is not yet prepared for as the lethal flood event that hit western Europe in July of 2021 showed. Urban areas in particular are vulnerable to floods because of their high population and infrastructure density. At the same time, urbanization has changed the hydrological status of the areas by building roads and buildings and destroying a country's natural flood defence and infiltration system in the process. The expansions of cities due to population growth only increase the risk of floods further by changing the flow path and state of the water.

City planners, therefore, need a way to test how the existing built environment as well as new urban plans will hold up against floods in the future to be able to build flood resilient cities.

1.2 Research statement

Based on the climate change problem that the Netherlands is facing, this graduation thesis will focus on formulating a process to develop a semantic **3D city model** and connecting it to the results of a **flood simulation model** to determine **the direct and indirect effect of future floods on a city and its inhabitants** based on a **Flood Resilience score**. Afterward, the potential of using the combined 3D city simulation model as a **model-based spatial planning support tool for city planners** to test their **new spatial design decisions** is explored. The focus of this research lies in evaluating the spatial plans of a city on its flood resilience before the actual event occurs.

Sub-questions that this thesis will answer are as follows:

Part 1: Developing a semantic 3D city flood model

- SQ 1: What are flood resilient cities and how can flood resilience be measured?
- SQ 2: What are suitable urban flood simulation models?
- SQ 3: Can the emerging technology of semantic 3D city models be used to support the evaluation and design of flood resilient cities and which 3D city model formats can be used for this research?
- SQ 4: How can the 3D city model be enriched with additional infrastructure and building datasets?
- SQ 5: Does the semantic model indeed include the additional information on buildings and infrastructure? *Validation*
- SQ 6: How can the results from a flood simulation model be added to the developed semantic 3D city model?

- SQ 7: How can the flood simulation output be fully connected to the data-enriched 3D city model and can the chosen flood scenario be visualized in the semantic 3D city model?

Part 2: Developing a Flood Resilience Score to evaluate the flood resilience of a city

- SQ 8: How can flood resilience be measured in the combined model?
- SQ 9: What are the effects of the future rainfall scenarios on a city and its critical infrastructure?

Part 3: Exploring the potential of a 3D spatial planning support tool for city planners to evaluate a city's flood resilience

- SQ 10: Can the combined model be used as a spatial planning support tool to allow city planners to test their designs against a city's flood resilience?
- SQ 11: How can urban plans be assessed in terms of flood resilience?

1.3 Research relevance

Flooding is a significant problem for many cities around the world, as it can cause significant damage to infrastructure and disrupt the lives of residents. In some cases, flooding can even lead to loss of life. It is also relevant because climate change is increasing the frequency and severity of extreme weather events, and designing cities that are resilient to floods can help to protect the safety and well-being of residents. Designing flood resilient cities can also help in reducing the economic costs of flooding by investing in infrastructure and strategies that can mitigate flood risks. As such, there is a growing recognition of the importance of designing cities that are resilient to floods. This thesis seeks to develop a semantic 3D city model that can help urban planners to evaluate the effects of a flood on a city to achieve just that; the designing of flood resilient cities.

One key benefit of semantic 3D city models is that they can be used to support spatial planning and decision-making. City planners and municipalities, for example, can use these models to evaluate the flood resilience of new environmental plans and make informed decisions about how to mitigate flood risks in their communities. Overall, this research aims to expose the relevance and importance of developing semantic 3D city models as they provide a detailed and accurate representation of a city, which can be used to not only support spatial planning and decision-making concerning the flood resilience of cities but also has the potential to facilitate an even wider range of (spatial) analytical research.

This thesis also strives to test the limits of a semantic 3D city model that is based on CityGML to identify any weaknesses or limitations in the model and allow for improvements to be made. In addition, testing the limits of semantic 3D city models based on CityGML can help to ensure that the model is 'fit for purpose' and meets the needs of the users. These arguments are especially important when the model is used as a basis for decision-making, as it is crucial to have accurate and reliable information. At the same time, this research also endeavours to test the usability of the semantic 3D city flood model using only publicly available data and software. By developing a 3D city flood model using open data and software, the model becomes more accessible to a wide range of individuals and organizations, benefiting them regardless of their resources or expertise.

Overall, this research attempts to reduce the research gap of semantic 3D city models by focusing on developing a semantic 3D city model in combination with a flood simulation model and a flood resilience score which can be used as a spatial planning support tool by city planners.

1.4 Reading guide

The thesis is made up of 3 parts (see Figure 1). Part 1 focuses on developing a semantic 3D city model that includes information on the geospatial location of a flood. Within the second part of the research, a Flood Resilience Score is developed followed by the exploration of a potential spatial planning support tool for city planners in part 3.

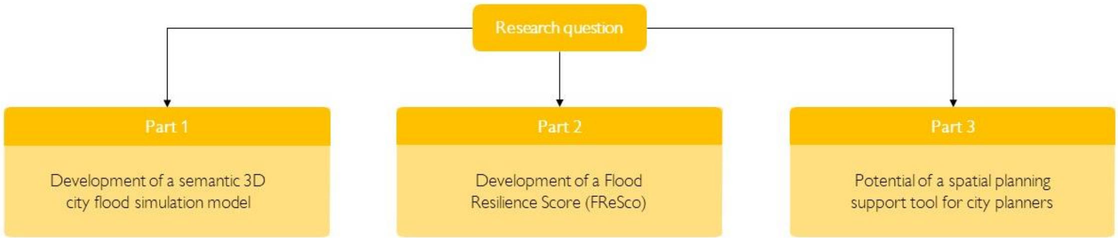


Figure 1. Simplified research design.

Following the introduction, a literature review is conducted to answer the first 3 sub-questions stated in Section 1.2 regarding flood resilience cities and their infrastructure (Section 2.1), the exploration of urban flood simulation models (Section 2.2), and the emerging semantic 3D city model technologies (Section 2.3). The research approach is then described in Chapter 3 including the research design (Section 3.1), the study area used for this research (Section 3.2), how the collected data is managed (Section 3.3), the software that is used to develop a 3D city flood model and the accompanying spatial planning support tool (Section 3.4), and the limitations that the research will face (Section 3.5). Next, the first part of the research as depicted in Figure 1 is conducted in Chapter 4. The development of a semantic 3D city flood model commences with the set-up of the 3D city model (Section 4.1), followed by the data enrichment of the 3D city model (Section 4.2) and the connection of the model to the results of a flood model (Section 4.3). A conclusion (Section 4.4) completes the development of the semantic 3D city flood model. Parts 2 and 3 are combined in Chapter 5 which focuses on the evaluation of the Flood Resilience Score. First, the Flood Resilience Score is developed (Section 5.1) followed by the evaluation of the results of the score (Section 5.2). To explore the potential of a spatial planning support tool for city planners, the tool is first developed (Section 5.3) and then the results of the tool and the Flood Resilience Score of the new environmental plan are compared to the former results (Section 5.4). In the end, Chapter 6 concludes the research by drawing a conclusion (Section 6.1) and evaluating the research in a discussion (Section 6.2) including points of improvement on the research itself (Section 6.3) and recommendations to other researchers, as well as decision-makers such as the government or municipalities (Section 6.4).

2. Theoretical framework

The following theoretical framework including a literature review focuses on answering the first 3 sub-questions of this research; 'What are flood resilient cities and how can flood resilience be measured?' (Section 2.1), 'What are suitable urban flood simulation models?' (Section 2.2), and 'Can the emerging technology of semantic 3D city models be used to support the evaluation and design of flood resilient cities and which 3D city model formats can be used for this research?' (Section 2.3). At the end of this chapter a conclusion is drawn (Section 2.4).

2.1 Flood resilient cities

2.1.1 A global need for flood resilient cities

According to the 2020 Global Risk Report by the World Economic Forum (2020), three of the top five risks that the world is currently facing - by both likelihood and impact - are related to climate, with risks from extreme weather events (including floods, fires, cold fronts, heat waves, windstorms, etc) scoring highest on the likelihood scale and 4th place regarding impact severity. Among extreme weather events, flooding is seen as one of the major contributors to economic damage and loss of human life. Worldwide, 44% of all recorded disasters between 1970 and 2019 have been associated with floods while 31% of the total economic losses and 16% of the total human losses during that period are attributed to flooding (World Meteorological Organization, 2021). Furthermore, the UN environment programme (2020) states that floods are going to become more frequent in the near future due to long-term global climate change making floods an even more serious threat. Already, global data on floods shows that increased flooding is happening everywhere in the world (FloodList, 2021).

Only recently did West Europe experience what it means to not be prepared for major floods. During the month of July 2021, the area depicted in Figure 2 was surprised by heavy rainfalls that lasted for several days. The heavy rainfall turned into lethal floods, costing the lives of at least 224 people. The government of the Netherlands (one of the affected but 'lucky' countries without any deaths) estimated the monetary damages in Limburg to be around 1,8 billion euros (Banach, 2021). This extreme weather event was a wake-up call for many highly developed and well-funded Western European countries that believed themselves to be well prepared and protected by, among others, the European Flood Awareness System.

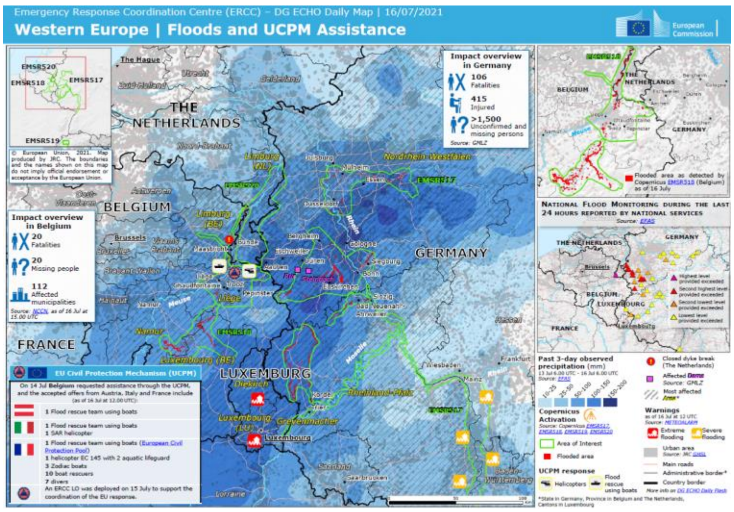


Figure 2. Map of floods in West Europe in July 2021 (European Commission, 2021).

Urban areas are especially vulnerable to floods due to their high population and infrastructure density. At the same time, urbanization is changing the hydrological status of urban areas and the flow path of the water by building new roads and buildings and destroying a city's natural flood defence system in the process (World Economic Forum, 2019; Zhi et al, 2020). One of these natural flood defence system is the soils capacity to absorb the excess water. In urban areas, however, the water infiltration rate of soil is too low because of soil compaction which leads to increased instantaneous flooding (Yang & Zhang, 2011). Instead of increasing the soils infiltration rate by incorporating more green belts for example, cities heavily rely on their man-made sewage systems to transport the excess water outside of the city.

Currently, around 3 out of 5 cities worldwide with a population size greater than 500.000 inhabitants are at risk of natural disasters (United Nations Department of Economic and Social Affairs, 2018). The consequences of a flood are manifold; landslides, shifting and sinking of the ground, structural damage to buildings, power outages, destabilization of (important) infrastructure, necessary displacement of whole cities, increased migration, etc all resulting in social, cultural, and economic losses as well as loss of (human) life.

The World Resource Institute (2020) estimates that by 2030, coastal floods will annually impact 15 million people worldwide and yearly damage urban property up to an amount of $177 billion. Meanwhile, riverine flooding - mainly resulting from heavy rainfall - are expected to lead to even more damage, globally affecting over 132 million people and costing $535 billion in urban property annually.

Building flood resilient cities is therefore becoming increasingly important to mitigate more extreme urban hazards, withstand the increased threats and recover from incidents more quickly.

2.1.2 Need for spatial planning support tool for city planners

The people and organizations that greatly influence the cityscape and inherently a city's resilience, are city planners and municipal policy makers when designing and adopting environmental plans. However, as city planners are - on average - no experts in fluid dynamics, it is assumed that they do not know how water will behave within their spatial design or what effect excess water will have on their spatial design or the surrounding city. A model-based spatial design-decision tool can support them in making spatial design decisions. By giving city planners a spatial design-decision tool to evaluate the flood resilience of their environmental plans, they can make sure that new urban designs can live up to their full potential in contributing to the flood resilience of the city.

Meanwhile, research papers on spatial planning support systems are manifold, but the systems themselves are relatively under-used in practice. Research by Vonk (2006) argues that this is the case due to several reasons. For one, while developers provide advanced systems, city planners demand simple systems. The main causes for the limited acceptance of these planning support systems are *"the lack of awareness of the existence and potential of PSS [Planning Support Systems], the lack of experience with PSS, and the lack of intention to start using PSS among the intended users"* (Vonk, 2006). Fortunately, the acceptance of spatial planning support tools within municipalities has been changing over the last few years. Municipalities and decision-makers are starting to use spatial planning support systems more frequently such as climate stress tests to prepare for the consequences of global warming (Deltaprogramma, 2017).

On average, early interventions in the design process take more time than in a traditional process but the benefits of using these tools beforehand (e.g. time-saving and reduction in planning mistakes and costs) later outweigh the additional time required at the beginning of the process (Pick, 2008). The time-effort distribution of implementing Building Information Models (BIM) (see Figure 3) for example shows that the bulk of the design process is moved to the preliminary design process as well as the schematic design process. While these phases require more time compared to the traditional design process where most of the workload is done during the construction documentation phase, the costs of design changes are kept much lower and the ability to still impact cost and functional capacity is much higher (MacLeamy, 2004). While BIM is 'only' used for individual buildings, a similar model such as a semantic 3D city model covering a much greater area could be utilized to help build flood resilient cities.

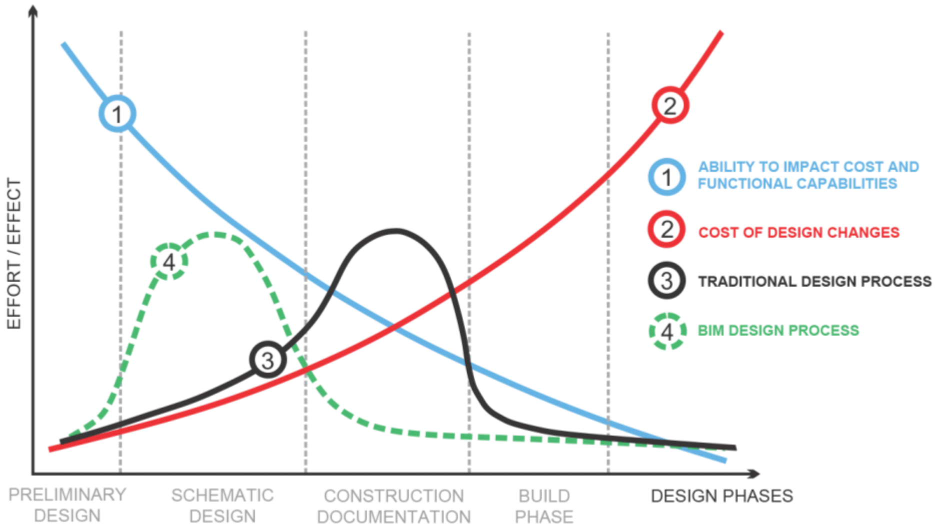


Figure 3. The time-effort distribution at the design stage for BIM-enabled and traditional AEC processes (MacLeamy, 2004).

2.1.3 Floods in general

A flood can be defined as an overflow of water that (temporarily) submerges usually dry land. In some rare cases, a flood does not consist of water but other fluids. Worldwide, floods are the most common and widespread natural disaster among all weather-related disasters which can last for just a few minutes or sometimes for weeks (NOAA National Severe Storms Laboratory, n.d.). Interestingly, while the media of western countries view floods as a nuisance and the word 'flood' has a negative connotation (and this thesis only contributes to that stigma), floods also play important roles in agriculture, civil engineering, and public health. Other countries such as Vietnam are much more aware of the benefits of floods and therefore have a more positive outlook on floods (McClymont et al, 2019). This research, however, will only focus on the effect that unwanted floods (will) have on the built environment, and not on the benefits of floods in general.

The occurrence of floods is strongly dependent on land use and its changes such as deforestation, wetland removal, flood control measurements, containment of or change in waterways, expansion of the built environment, climate change, and sea level rise. When observing floods, it becomes clear that they result from one or a combination of the following events; heavy rainfall, melting snow, obstruction of waterways, soil impermeabilization (resulting from urbanization or droughts), broken dams or dikes, and high tide. Losier et al (2019) define six different types of floods;

1. *Flash floods*; are events where an area is quickly flooded within less than six hours, usually caused by heavy rainfall and fast runoff. The intensity of a flood, its location, and distribution, as well as the affected area's land use, topography, vegetation, soil type, and population density, are all factors that influence if and how quickly a flash flood occurs and the extent of the flood.
2. *Urban floods*; refers to flooding in a - mostly densely populated - built environment. The lack of infiltration possibilities and the great number of impervious surfaces in a city, lead the water to run off more quickly to the lowest point in the affected area, increasing the amount of water on the surface. The water flow of an urban flood is difficult to predict due to urban features such as a complex drainage network and obstacles such as buildings or walls and a variety of land uses with different rates of infiltration.
3. *Fluvial/river floods*; happen when the maximum capacity of a river is reached and water is breaching the riverbanks and overflowing the river's surrounding area. River floods can for example result from heavy rainfall, snowmelt, or the failure of a hydraulic structure such as a dam.
4. *Coastal/onshore floods*; mainly affect lowland coastal areas and often result from storm surges. Here, the severity of the flood depends on the storm's strength, size, speed, and direction. Other potential causes for onshore flooding are high upstream river flow or high tide. The severity of the flood is also dependent on onshore and offshore topography.
5. *Pluvial/rain-related floods*; result from either intense rainfall that overwhelms the urban drainage system leading the system to backlog and flood a city, or run-off or flowing water from rain falling upstream where the upstream area is unable to absorb the water. Pluvial floods are typically only a few centimetres deep but can result in large property damage.
6. *Compound flooding*; is specifically related to urban areas and can be a result of a combination of the types of floods listed above. Compound flooding is complex as excess water can enter a city via rivers, rainfalls, storm surges, and through a rise in sea level. At the same time, the water is retained in the city because of soil sealing.

The Netherlands experienced a devastating coastal flood on February 1st, 1953 that originated from a storm surge and dike failure and resulted in the total loss of 2395 human lives. This event was a turning point for the Netherlands to actively start fighting the water, heavily investing in a flood resistant country and planning and building artificial flood protection. Along the way, the Netherlands has become one of the major players in the world regarding water management. However, when it comes to increasingly heavier and more frequent rainfalls and the urban fabric that plays a key role in the resulting floods, the Netherlands is much less prepared as the events of the summer of 2021 have shown.

2.1.4 Definition of flood resilience

Floods cannot always be prevented. However, the impact of a flood can be mitigated or reduced by following resilience principles. Over the last few years, the concept of flood resilience has become much more urgent due to climate change which has inherently stoked the interest of researchers, governments, and companies alike. This has led to a variety of definitions, measurements, and applications.

The term resilience was first coined by Holling (1973) who introduced the term in the field of ecology. Later it was also used in social sciences, psychology, and disaster management. At its core, resilience can be defined as *"a system's ability to resume functionality in the wake of a perturbation"* (McClymont et al, 2019). Hodgson et al (2015) elaborate on the definition and also include the ability of a system to resist a perturbation or the time it takes for the system to recover after being disturbed. So an urban area is more resilient if its vulnerability to potential damage from flooding is low.

Until recently, cities' flood policies focused on flood resistance strategies that minimize the probability of flooding. This strategy entails that the frequency of flooding is reduced by for example river training, constructing embankments, or raising dikes. However, in the wake of climate change, unexpected climate perturbations have been occurring more frequently and flood resistance strategies are not great at coping with these uncertainties (De Bruijn, 2004a). Furthermore, flood resistance strategies apply one design discharge to a whole area (like the Netherlands) which means that there is no distinction made between the probability of flooding for different land use types. By implementing only one safety level, it is unclear which parts of the area will be flooded when the capacity of the artificial protection is exceeded. Overall flood resistance strategies give little attention to the consequences of possible floods while potential flood damage is increasing. The false sense of safety for floods can lead to large economic investments in areas that are actually at risk of flooding, which is the case in the Netherlands (Vis et al, 2003). In case of a flood, the loss of economic value in the Netherlands will be great. The last disadvantage of flood resistance strategies that Vis et al (2003) list, is related to the inevitable rise in sea levels. With this inevitable event looming in the near future, the water defence structures that are now protecting the dry land will have to be raised and improved which will not only require another engineering world wonder (Briaud, 2021) but also an exuberant amount of money (Bregman, 2020).

In recent years, the resistance strategy has been subject to debate due to its disadvantages listed above. Alternative strategies have been explored culminating in the introduction of flood resilience concepts; *"the ability of a system to persist if exposed to a perturbation by recovering after the response"* (Vis et al, 2003). Plate (2002) follows by stating that it is more important to minimize the impact of flooding rather than to improve the existing flood defence construction. This practice is called Resilient Flood Management which increases the ability of the area to recover after a flood. A shift from Flood Resistance Strategies to Flood Resilience Strategies can also be seen in the change in cities' flood policies. Instead of fighting floods, cities are now focused on living with and minimizing the impact of floods by for example improving the permeability of the soil and leaving more room in the urban fabric for urban green spaces. So at its core, resilience is the opposite of resistance. According to Vis et al (2003), flood resilience is a matter of different measures to reduce the impact of floods. The development of warning systems and evacuation plans as well as risk awareness, flood preparedness, and financial preparedness like damage compensation regulations and insurances are important aspects of a flood resilience strategy. Adequate land use and the application of spatial planning and building regulations is another important matter to minimize the impact of inevitable floods. Overall, land use concepts should be defined for areas that are prone to flooding. Also, setting and enforcing strict building regulations such as building codes and zone ordinances will set minimum acceptable requirements necessary to protect people and their property and regulate land use, respectively.

Overall, flood resilience is evaluated, developed, and achieved by learning from past events and adequately preparing for future ones (Xian et al, 2018). However, the Netherlands is one of the countries that will suffer and even already has suffered major human and economic losses when the artificial protection systems fail or flooding occurs due to heavy rainfall (Banach, 2021; Rijkswaterstaat, n.d.). Therefore, some kind of model is needed so that these real events do not first have to be experienced by the country and its population but potential flood events and their effect on the built environment can already be simulated beforehand to take measurements accordingly.

2.1.5 Critical infrastructure networks and points to manage floods

During an urban flood, critical infrastructure plays an important role in either preventing or mitigating the extreme environmental hazard or accelerating the disaster even further. So what are critical infrastructure networks? The Commission of the European Communities (2006) defines critical infrastructure as *"infrastructures whose services are so vital that their disruption would result in a serious, long-lasting impact on the economy and society"*. According to the Deltaprogramma Ruimtelijke Adaptatie (2014), the Netherlands classifies its critical infrastructure into 7 functions; energy, telecom/ICT, water network, health, surface water, transportation and chemicals, and nuclear plants. So - for example - while a high-quality power and transportation network can help mitigate the disaster, the collapse of crucial infrastructure nodes such as power plants and transportation hubs can also lead to the loss of life and socio-economic damage beyond the impact of the actual hazard.

In her graduation thesis, De Jonge (2021) assesses five critical infrastructure networks during heavy rainfalls, a rainfall of 18,9mm in one hour expected to occur every two years and a rainfall of 35,7mm in one hour expected to occur every ten years. The five critical infrastructure networks in question are;

1. Road network
2. Electricity network
3. Mobile network
4. Accessibility to hospitals
5. Accessibility to supermarkets

De Jonge (2021) uses the road network and the electricity network to quantify the resilience of the infrastructure of the Hague.

Meanwhile, the Delta Programme 2023 (Deltaprogramma, 2022) lists thirteen national vital and/or vulnerable functions, that each belong to an infrastructure network which is crucial to the flood resilience of cities. One of these functions is health and the public health network which focuses less on flood resistance, as the other critical infrastructure networks listed above, and more on the resilience of cities and their networks. This network ensures that the inhabitants of a city are supplied with all the necessary goods and services such as food, clean water, shelter, hygiene products, disease control, emergency responses, electricity connection, public transportation, and public order that are needed to survive during (flood) disasters. Therefore, the public health network is added to the list of critical infrastructure networks.

Within these critical infrastructure networks, there are physical infrastructure points that - during a flood – can be classified as either vital, vulnerable, or dangerous to the functioning of the city and the health of its inhabitants. This thesis compiles a list of potentially important physical infrastructure points within a city that city planners should take into account when formulating new plans and strategies. Critical infrastructure points are seen as either key entities of a network or important end-users of the critical infrastructure networks listed above. To compile the following list of critical infrastructure points, several major flooding events and their effects on the city and its people were investigated including the major flood that followed Hurricane Katrina in 2005 (Colten et al, 2008) and the pluvial floods in northern Europe in the summer of 2021. Additionally, the national vital and vulnerable functions in accordance with the Delta Programme are taken into account (Kennisportaal Klimaatadaptatie, n.d.).

1. Vital infrastructure points (that are also vulnerable when affected by a disruption):
    - Hospitals
    - Fire stations
    - Police stations
    - Supermarkets
    - Electricity boxes
    - Telecommunication masts
    - Fresh water taps
    - Public transportation hubs
    - Distribution centres
    - Bridges
    - Municipality buildings (eg. city hall, municipal utility yard)
    - Sewage pits
2. Vulnerable infrastructure points (that do not directly contribute to a city's flood resilience):
    a. Hospitals
    b. Nursing/elderly homes
    c. Electricity boxes
    d. Bridges
    e. Monuments and world heritage
    f. Education centres
    g. Office buildings
    h. Residences
3. Dangerous infrastructure points (that can have a potentially disastrous effect when disrupted):
    a. Sewage pits
    b. Energy (nuclear) plants
    c. Storage of hazardous substances

Nowadays, infrastructures are highly interconnected and dependent on each other (see Figure 4). These infrastructure network dependencies can be divided into 4 types; physical, cyber, logical, or geographical (Rinaldi et al, 2001). In a highly complex built environment with countless entities and relationships, these complex interdependencies lead to so-called 'cascading effects' during disturbances such as a major flood (Zimmerman & Restrepo, 2009). An example of a cascading effect would be a public electrical box being flooded leading to an electricity network failing in the surrounding area which leads to the telecommunication network going down, which means that first responders such as police officers or firemen/women cannot be contacted which results in false or no deployment of first responders to the disaster sites.

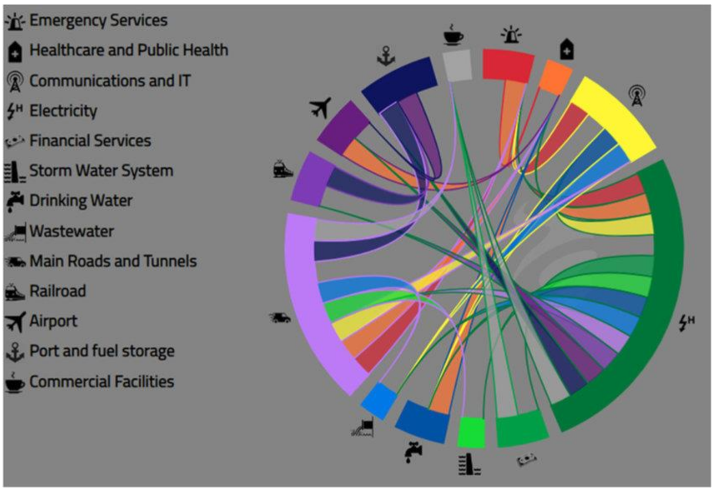


Figure 4. Illustration of the critical infrastructure dependencies in a circle diagram (de Bruijn et al, 2019).

The infrastructure networks make sure that our everyday life is safe and runs as smoothly as possible without any uncomfortable interferences. However, current infrastructure is designed for historic climate conditions. It can therefore be expected that in the future, already existing infrastructures will become more vulnerable to extremer and more frequent weather events (Auld, 2008). This inherently means that the state of infrastructure will decrease more rapidly or even cease to operate, plunging a city into chaos. Besides maintaining a city's critical infrastructure, the effect that a future urban flood can have on the interdependent infrastructure networks and the resulting cascading effect from this event needs to be investigated to be able to build cities that are more resilient to floods.

Carrying out stress tests to identify which critical infrastructure networks are vulnerable is also the first of six proposed steps in the Dutch roadmap to protect critical infrastructures from disruption of hazards (Bles et al, 2020). This is followed by analysing the impact of such a network if it is disrupted, identifying possible cascading effects, and determining the most important risks. These first 4 steps of the roadmap could in theory be executed by using a digital twin in combination with a flood simulation model.

2.1.6 Measuring a city's flood resilience

The Resilience Shift (n.d.) provides a Resilience Toolbox that includes 29 different tools related to the resilience of cities. These tools range from an open source urban simulation system to a training concept to improve the resilience and adaptive capacities of users, to the City Resilience Index developed by Arup and the Rockefeller Foundation which serves as a planning and decision-making tool for cities concerning urban investments. This City Resilience Index with its 52 indicators focuses primarily on systems, institutions, and policies, while people and the resources available are less important (Leandro et al, 2020).

Overall, many methods exist to measure resilience but there is no consensus on which measurement method is best, especially because each tool defines resilience slightly differently and different entities of the built environment are taken into account (De Bruijn, 2004b). Another potential reason why there is such a great variety of tools could be because the resilience of cities and their (critical) infrastructure networks can be evaluated during different temporal phases (De Jonge, 2021; Li et al, 2019). Before an event occurs, one can evaluate the preparation plans for the potential event, during the event, the city's resistance, absorption, and accommodation potential can be tested, and after the event, the recovery time can be calculated to see how long it takes for a city to get back to its steady state. In the end, the choice for flood resilience indicators to quantify the effect of a flood comes down to the availability of data. This research will therefore create its own method.

The focus of this research lies in evaluating the spatial plans of a city on its flood resilience before the actual event occurs. There are two main ways to analyse an urban flood, by visualizing the extent of the flood or by quantifying the effect of the flood on the city in a score or index.

Assessing through visualizing floods

So far, city planners mainly use flood maps that are generated by flood simulation models to see which urban areas are in danger of being flooded. There are many tools available that can visualize the water level in the built environment during a certain moment in time. Figure 5 depicts different examples of flood visualizations that show the extent of a flood. Using flood maps, city planners are able to draw visual conclusions regarding the flood resilience of spatial plans, such as the location of the most affected areas within a city and the depth and velocity of the floods which indicates the most endangered areas within a flood. What the visualization of a flood does not show, however, is the effect that a flood has on a city and its infrastructure. The visualization of a flood does not automatically generate a list of all the buildings that fall within the flooded area, color-coding the buildings that are most vulnerable, dangerous, or vital to citizens, nor does the visualization takes into account that a flood can also have an impact on the area surrounding the flood. To quantify a city's flood resilience, different tools are required.

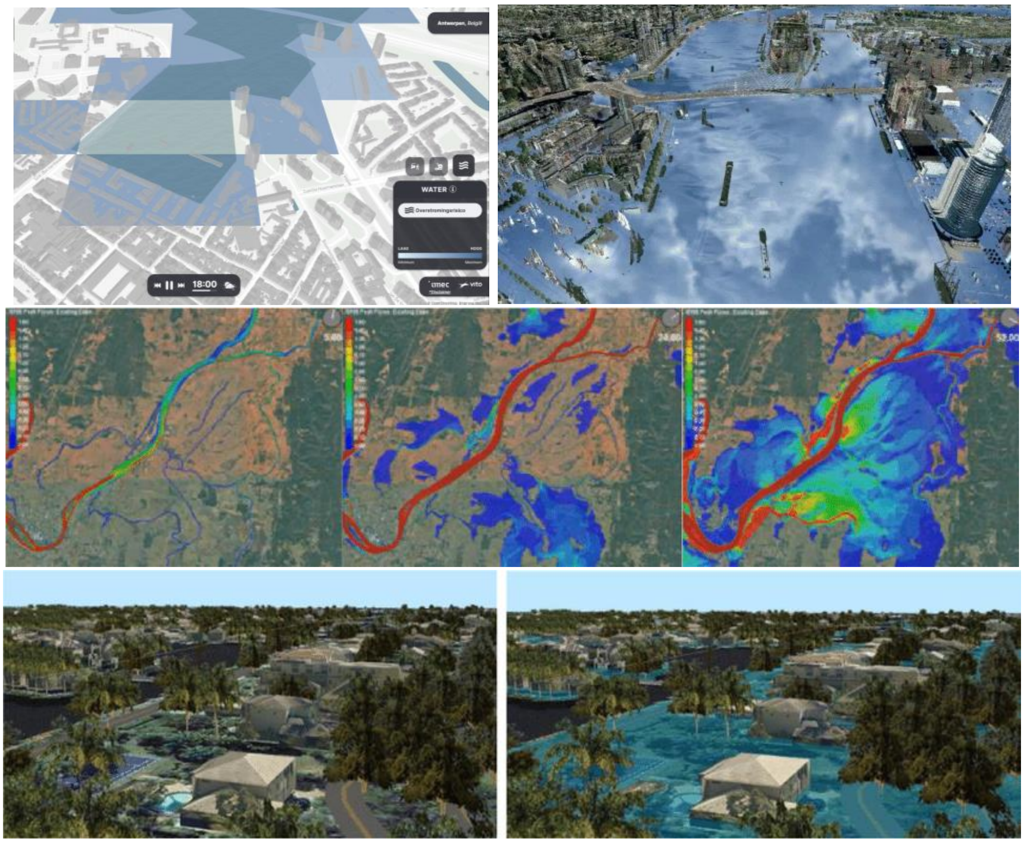


Figure 5. Visualization of a flood scenario in the Demo Digital Twin of Antwerp (IMEC, 2018) (top left), a rainfall data visualization in Rotterdam (Leskens et al, 2017) (top right), a flood model simulation of TUFLOW (Van Ackere et al, 2016) (middle) & a 3D GIS visualization of a flood in Broward County, U.S. using Esri's ArcScene software (DeVito, 2015) (bottom).

Assessing through quantifying flood resilience

Quantifying and assessing the impact of an urban flood to draw a conclusion on the flood resilience of a city is not a straightforward method as the literature review by Hammond et al (2015) shows. There is a variety of researchers and institutions that mainly focus on the tangible impacts of a flood such as loss of live, number of people rescued, injuries sustained, cost of damages, and value of lost production. Impacts of a more intangible nature are much more difficult to assess and quantify. Indicators such as damages in regards to someone's means to pay for them, the long-term impact on peoples' physical and mental health, or resulting infections are much more difficult to quantify (Hammond et al, 2015).

Socio-economic, socio-technical, and human factors are involved in measuring resilience and the unpredictable extent of flood events makes flood models non-linear and complex (Davidson et al, 2013). There are a few, however, that try their hand at assessing flood resilience. Oladokun et al (2017) for example developed a fuzzy logic-based resilience measuring model using three input factors; inherent resilience, supportive facilities, and resident capacity. The research findings resulted in a fuzzy inference system that generates resilience indexes for households. In the meantime, Leandro et al (2020) propose an event-based scalable Flood Resilience Index for assessing climate change adaptation. According to the authors, the developed Flood Resilience Index is capable of identifying households and districts in the city of Munich, Germany that are (1.) most affected by heavy rainfall, (2.) will benefit the most from household climate adaptations (adding a flood-proof gate with an indoor tank and a submersible pump system), and (3.) identifying the most resilient households and districts. Zhang et al (2021) makes use of the entropy-weighting TOPIS method – a multi-attribute decision method to approximate the optimal solution - to diagnose flood resilience of 31 key flood control cities in China. First, urban disaster resilience was divided into four dimensions; economic, social, environmental, and management. Then, within these dimensions, 18 assessment factors that affect urban disaster resilience were identified, a judgement matrix was set up, and each indicator was weighted according to the entropy weight method to calculate what kind of impact the indicators have on city flood resilience.

These researches have in common that they all produce some kind of flood resilience score. What the researches do not do, is to get an overview of the effect that a flood has on a city to establish the resilience of a city. A city model in combination with a flood simulation model which facilitates querying, can display the effect of a flood on a city while serving as a spatial planning support tool for city planners by taking into account the importance of certain infrastructure points during a flood.

2.2 Inventory of flood simulation models

Floods, especially in urban areas, are overly complex and chaotic due to the phenomenon of 'compound' flooding where water 'enters' the city from several points of origin, such as rivers, rainfalls, and storm surges and where it is retained due to soil sealing (Losier et al, 2019). Spatial planning decision-making to prevent, mitigate and manage 'complex' floods is therefore needed to build the flood resilient cities of the future. However, to do so, floods first need to be modelled.

Throughout human history, people have been trying to understand, predict, mitigate, and utilize floods. But only since the 1970s, with the help of computational power and technological advances, researchers have been able to vastly improve flood inundation models, which has led to the development of a substantial number of models. Overall, with these new developments, researchers were given a more detailed insight into the behaviour of water, identifying among others the location of floods, flood areas, flood depth, and the velocity of the water. Flood inundation models can be used for many purposes; for example, flood risk mapping, flood damage assessment, real-time flood forecasting, flood-related engineering, water resources planning, or investigating river bank erosions and floodplain sediment transport (Teng et al, 2017).

A model should be carefully selected based on the demands of its end-user. Teng et al (2017) sort the vast number of models into 3 categories; empirical methods, hydrodynamic models (including 1D, 2D, and 3D models), and simplified conceptual models. Models based on empirical methods use observations and historical data to reconstruct floods and therefore reflect the past rather than the future. This also makes the models more accurate and robust than other models and allows the model's output to be used as input in other models. However, because inputs cannot be manipulated (as they are based on past events), the model cannot be used to investigate the impact of changes. Meanwhile, hydrodynamic models are mathematical models that replicate fluid motions in either 1D, 2D, or 3D. 1D models treat a flow as one-dimensional along a centre line that only goes in one direction. These models are used to represent the flow going through a pipe or confined channel or to model an open surface floodplain flow. As the name indicates, 2D models model floods in a two-dimensional field. The third dimension that is not considered is the water depth which is assumed to be shallow. 3D models do however take vertical features such as the depth of water into account which makes it possible to model vertical turbulences, vortices, and spiral flows at bends. These features make 3D models highly attractive for modelling catastrophic floods. The last category, the simplified conceptual models, are models that do not use complex mathematical equations but rather simplified hydraulic concepts such as the bathtub method (Teng et al, 2017). This also means that they run faster than the hydrodynamic models and are more suitable to run simulations but they cannot be used to investigate dynamic effects.

According to Teng et al (2017), while empirical methods are sufficient for monitoring floods or assessing flooding disasters after they have happened, hydrodynamic models can be utilized to assess the extent of a flood - resulting from for example a dam break, tsunami, or flash flood - by changing the model's input parameters. Due to their characteristics, 2D and 3D hydrodynamic models are suitable for modelling floods in urban areas. 1D hydrodynamic models, however, are incapable of simulating the lateral diffusion of a flood, meaning that urban obstacles such as buildings cannot be taken into account. Meanwhile, simplified conceptual models are suitable for probabilistic flood risk assessments or multi-scenario modelling on a large scale (floodplains greater than 2.000km^2). Based on the study by Teng et al (2017), it becomes clear that hydrodynamic models and in particular 2D and 3D models are best suited to simulate an urban flood.

Simulating an urban flood, however, is not enough to evaluate the flood resilience of a city as it only gives information on the flood itself. Before flood resilient cities can be built, a city and its infrastructure first need to be modelled which requires a great amount of data on the city itself (Hammond et al, 2015). The flood modelling results can then serve as simulation input into the virtual city model to assess the damage that the urban flood caused.

In the past few years, research has mainly used 3D city models to visualize floods. Kumar et al (2018) for example tried to give a more realistic interpretation and assessment of a flood in Delft by using Cesium 3D webglobe to layer a 3D city model on top of the open-source flood simulation tool Anuga to visualize the flood in a 3D city model. However, the research did not specifically take spatial information into consideration during the flood simulation process. According to Zhi et al (2020), when modelling floods, only limited consideration is given to 3D spatial information. To find out if 3D spatial information has an influence on flood modelling, the authors combined an urban drainage model and a flood simulation model with 3D visualization methods and 3D building models. Their results showed that details on buildings and infrastructure indeed need to be added to flood simulations as they play a vital role in the distribution of floods throughout a city. Furthermore, while improving the interpretability of flood model data, the visualization of urban floods only gives limited information on the actual effect of a flood on a city. In 2021, Ghaith et al tried designing a framework to *"devise a city digital twin under flood hazards through the integration of data acquisition systems, hydrology and hydraulic modeling, physical infrastructures and entities, demographic information, and real-time system behavior"* using the city of Calgary, Canada as a study case. Based on this framework, digital twins should be able to imitate floods and their impact on a city's infrastructure, identify vulnerable locations in the city during a flood, increase a city's flood resilience, and develop strategies to mitigate the risk of floods. In the end, the researchers were able to visualize an urban flood in the centre of Calgary in a 3D city model and query the number of buildings and sections of road that were affected by the flood including their corresponding inundation depth.

So far, the existing models are only able to show a small number of localized effects that an urban flood can have on a city, such as the location of the flood and the water depth and velocity at a specific location. However, urban floods have much greater impacts on a city than just flooded buildings as any real disaster has shown. Most of these impacts have to do with cities' critical infrastructure networks and points.

Flood models are yet incapable of identifying the direct as well as indirect effects of a flood on a city's infrastructure and its inhabitants as they are missing important information on the urban environment itself that goes beyond the geometries and infiltration rates used for flood simulation models. By connecting a flood model to a semantic 3D city model which is capable of handling a great amount of urban data, the flood resilience of a city could in theory be identified.

During a COP26 webinar, the Centre for Digital Built Britain of the University of Cambridge presented CReDo, their web-based and open-source Climate Resilience Demonstrator, which is meant to consider the cascading effects resulting from floods (National Digital Twin Programme, 2022). The focus of CReDo is on modelling the country's infrastructures and the interdependencies among them in a 2D model. Currently, the demonstrator only uses urban data of a fictitious city and can only simulate one pre-programmed flood scenario with a handful of prescribed implementation choices and their ranked monetary costs and resilience score (see Figure 6).

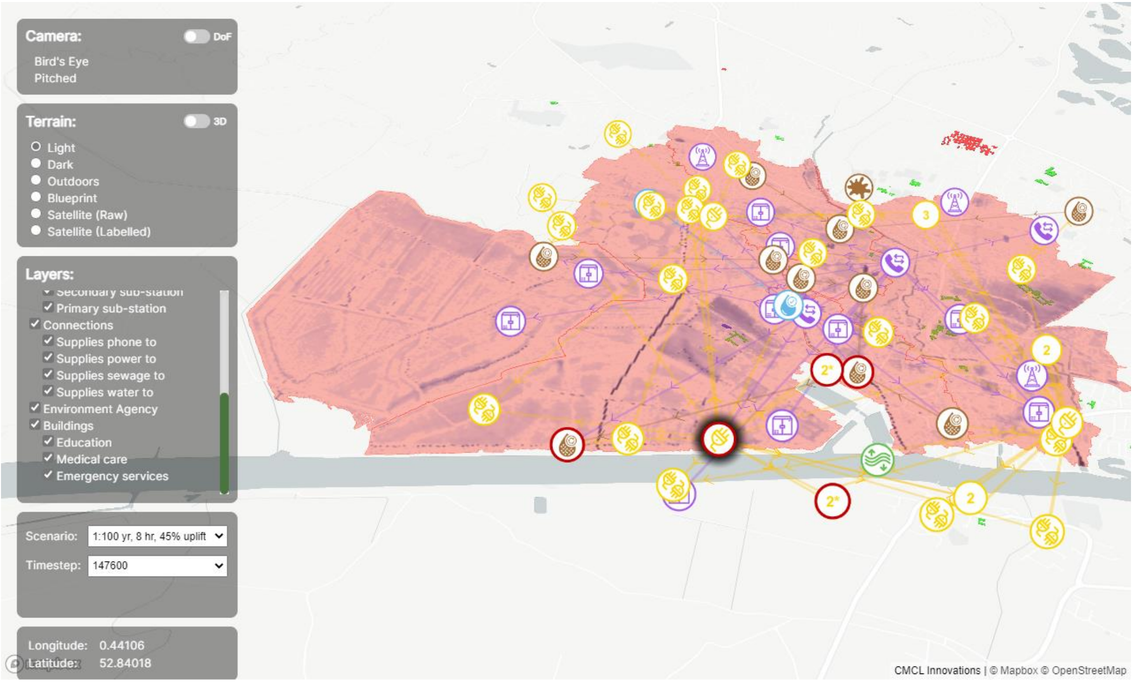


Figure 6. CReDo visualization (Digital Twin Hub, n.d.).

In the meantime, the Dutch company Movici has been developing a more complete 3D model of the Netherlands and its critical infrastructure which takes into consideration the countries road-, train-, electricity-, gas-, sewage-, and telecom network as well as its air- and seaports. The interconnectedness between the infrastructures is modelled and potential scenarios of the future are simulated and visualized. Figure 7 shows an example of the 'impact' interface from the software platform SIM-CI (now known as Movici) which measures the potential cascading effects of a sluice break in the Hague. Currently, however, Movici's simulation model is unable to layer a flood simulation model over their 'System of Systems' model to show the cascading effects of an urban flood.

Figure 7. User interface of the SIM-CI software platform (NGInfra, n.d.).

2.3 Semantic 3D city models

Cities are made up of complex and dynamic systems of elements that are spatially and intrinsically connected to each other. Sometimes these relationships are clear, other times they are hidden and only discovered during the disruption of a system. For a human, it is impossible to fully understand the intricate workings of a city. At the same time, with a large amount of the global population already living in cities and the shift to move to cities continuing, cities have become even more complex.

In a technology-driven and ever-growing world, meticulous planning is needed in light of climate change and industrialization. The utilization of urban analyses and planning tools is becoming more pressing to make well-founded spatial planning decisions but cities have also become more complex to model. To understand and manage dynamic and complex cities, semantic 3D urban models need to be developed that reflect these characteristics. Semantic 3D city models are a promising, newly emerging type of data-driven base model to conduct complex urban analyses with. The technology of reconstructing environments has significantly increased over the last decade and more and more municipalities, local and national government surveying agencies and commercial companies are building their own 3D city models. These models can even take a crucial part in the intelligent management of cities.

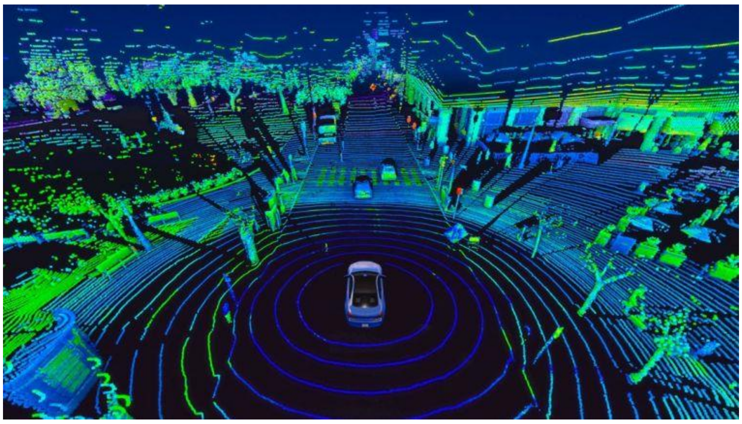
In essence, a basic 3D city model is a digital representation of the built environment. Recent research has been focusing on exploring the potential of integrating urban information into these models so that a city is not only visualized in 3D but also facilitates computer-based urban spatial analyses. In theory, these so-called 'Urban Digital Twins' could not only make use of the 3D visualization of a city but also link sensor data, historical data, infrastructure data, etc to a specific location in the digital twin, all while representing the built environment in real-time. For now, though, research is focusing on integrating more urban data into 3D city models - called semantic enrichment or data enrichment - without adding a real-time element.

These semantic 3D city models go beyond visualizing the built environment as they have the potential to become integrated information models that can be used for many different urban spatial analyses. They can be used for complex GIS simulations and analysis tasks such as urban planning, environmental and training simulations, noise propagation simulation and mapping, (indoor) navigation, telecommunication planning, disaster management, emergency responses, or energy-related applications (Gröger & Plümer, 2012; Yao et al, 2018). Wate and Coors (2015) try to use 3D data models to simulate the overall energy flow in urban areas while Kaden and Kolbe (2013) estimate the total energy demand of buildings in the city of Berlin using semantic 3D building models. Furthermore, according to the European Commission (2020), benefits from digital twins (read 3D city models) are manifold and vary from cost efficiencies, operational efficiencies, better crisis management, better information decision-making, and better urban planning, to more participatory governance.

Currently, the interest in and application potential of semantic 3D city models is great. But while municipalities are developing their own 3D city models, they often do not fully exploit the potential of these models. At the same time, having stakeholders develop their own version of a 3D city model creates stand-alone models that are not interoperable with other 3D city models (Stoter et al, 2020). This makes scaling up nearly impossible and limits professionals in making well-informed urban decisions.

2.3.1 3D city model technology

These days, large-scale 3D urban models are made possible thanks to advances in technologies such as aerial vehicles, tilt cameras, lidar equipment, and high-resolution stereoscopic imaging as well as progress in fields such as remote sensing, photogrammetry, computer graphics, stereo vision, and machine learning (Früh & Zakhor, 2004; Hu et al, 2003; Jie et al, 2019). Furthermore, companies such as Apple, Google, and Microsoft have a stake in the 3D graphic information market which drives the development and improvement of public mapping services forward. The appearance and system architecture of 3D models varies based on the acquisition techniques used, their structure, format, and characteristic. 3D models can be reconstructed using for example photogrammetry, laser scanning, extrusion from their 2D footprint, conversion from architectural models and drawings, procedural modelling, or volunteered geoinformation (Arroyo Ohori et al, 2022). In addition, Jie et al (2019) and Duan and Lafarge (2016) list satellite imagery including high-resolution satellite imagery and microsatellite imagery, as well as ground data, and crowd-sourced data as additional urban modelling data sources to acquire spatial data from. In the long list of data sources, LiDAR and photogrammetry are specifically used to collect 3D elevation information of the terrain and the building objects.



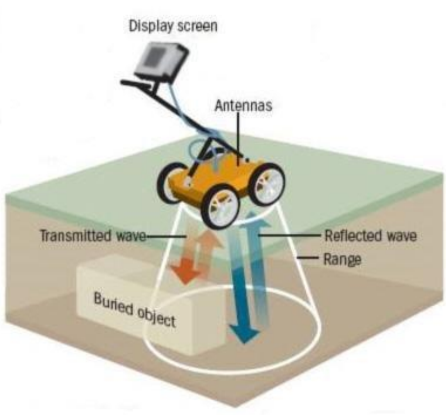


Figure 8. LiDAR scanner used for mobile mapping systems (Alsadik, 2020) *(left).*

Figure 9. Obtaining ground data using a Ground Penetration Radar (GPR) (Abdulrazzaq, 2017) (right).

Figure 10. Photogrammetry carried out with drones (Prior, 2022).

The process of constructing 3D urban models can be done manually (which is labour-intense and expensive but leads to the most accurate models), semi-automatically or automatically. Nowadays, the last two options are made possible thanks to photogrammetry and laser scanning technologies which make it easier to model large-scale urban areas but also lead to less accurate models.

The automation process of 3D urban modelling uses a few key technologies; point cloud generation, surface reconstruction, texture mapping, and the modelling of multi-source data fusion. Point cloud generation refers to the technology of matching and reconstructing stereo image pairs using a dense point cloud (Borisov et al, 2022). During the feature matching process, feature points are extracted from an image and matched. Often, the point cloud requires intensive reconstruction which means going from calibrated pairs and sparse point clouds to a much denser point cloud. The surface reconstruction technology accurately reconstructs the geometries and topographies of the model. This reconstruction is needed because the density of point clouds is uneven and there are different degrees of occlusion and self-occlusion (Kedzierski & Fryskowska, 2015). Other problems with point clouds that require surfaces to be reconstructed are the shadows, void areas, and the great number of noise points that 3D cloud points produce. These problems make it nearly impossible to recover 3D models from imperfect point clouds (Jie et al, 2019). Another technology that is used in 3D urban automation modelling is texture mapping. This technology uses a texture reconstruction method to add texture to the 3D model and at the same time resolves image colour differences that occur during scanning due to changes in the weather or lighting (Frueh et al, 2004). However, only overlapping a textured mesh with aerial images makes the 3D city model look realistic, however, no queries can be run to answer substantive questions such as 'How many buildings are in the model?', 'How many floors does a building have?', or 'How many trees are in the urban area?'. Often, multiple data sources are used for urban modelling like the fusion of LiDAR data and aerial image data.

According to Jie et al (2019), in the future, there are still three main challenges to overcome in the process of urban modelling. The first challenge is regarding the limitation of data acquisition. It is not only difficult to obtain complete and comprehensive data of cities in crowded areas, but the obtained data often includes futile information about temporary objects such as vegetation, animals, vender stands, a variety of vehicles, or pedestrians. Furthermore, reflective surfaces such as glass facades act like a mirror which leads to a reduction in the density of the data obtained. The second and third challenges that Jie et al (2019) refer to are the translation of the complex optimization process to reality and the scalability and quality of the building model during the optimization process. The variety of urban reconstruction methods is increasing, but their scalability to larger urban environments is still difficult and often goes hand-in-hand with a reduction in quality during the optimization process.

While data sources and urban modelling technologies are ever progressing, a variety of 3D modelling software and tools have emerged, such as the sketch-based 3D modelling software SketchUp, the urban modelling software Esri CityEngine, the open source 3D modelling software Blender and Autodesk, and the 3D design software AutoCAD, Revit and SolidWorks.

Meanwhile, the variety of 3D urban models and the lack of unified modelling and coding standards have been leading to 3D models being created in different data formats (Stoter et al, 2020). As a result, 3D models are incompatible with each other prompting poor reusability, difficult information exchanges, and low utilization in 3D GIS systems. Overall, the lack of unified modelling and coding standards results in even more challenges for 3D models on top of the many other challenges the new technology faces (Hamilton et al, 2005). Interoperability between the 3D urban models is necessary to inherently reduce the cost of 3D model production and maintenance and to make information exchanges and the scalability of 3D urban models a reality (Stoter et al, 2020). However, this interoperability between 3D urban models is and will very likely remain impossible for it implies that different data sources and data qualities will have to be brought together and their content will have to align perfectly.

2.3.1.1 Semantic 3D city models

Most of the 3D city models that are currently being developed represent a simplified version of the built environment in geometrical or graphical form which can be used to visually explore a city. However, these models disregard the semantic and topological relationships of and between objects in the 3D city model. For example, point clouds and 3D meshes (which are used in computer graphics and gaming), are all used for the visualization of the built environment and can therefore be utilized for visual analyses. However, they do not contain information on buildings except for the characteristics of the built environment that the viewer can see. This makes quantified spatial analyses, thematic queries, and spatial data mining impossible.

Semantic 3D city models not only visualize the built environment but also label relevant objects and include the attributes of the geometries. They store objects, their components, their attributes, and the relationships between the different objects in an ontological structure to facilitate complex spatial analysis operations (Kolbe, 2009). In other words, a data model is added to the 3D city model where 'visual' objects are connected to additional 'hidden' information. According to Arroyo Ohori et al (2022), *"a data model is a high-level formalized way to structure information, generally using a set of abstract classes, relationships between them, and attributes to store information about them"*, where classes are often the spatial representation of the real world. These data models follow a certain standardized structure, also called a schema; which in essence is a descriptive document that formulates the data model, decomposes the model into (hierarchical) classes, and prescribes the classes and attributes so that the data models become interoperable. Essentially, a semantic 3D information urban model should allow the integration of multi-source heterogeneous geographic information into one framework (Jie et al, 2019).

2.3.1.2 Challenges facing 3D city models

Currently, the building industry sees 'digital twins' of cities as a potential answer to any question regarding urban planning. However, developing urban digital twins is still in its early stages. There is no consensus on the purpose of a digital twin, what a digital twin should look like, what kind of datasets should be included, what kinds of data formats the digital twin should have, how citizens' privacy can be protected, et cetera. Until this day, the term remains a catch-all for a collection of datasets within a 3D city model including a real-time element. Stoter et al (2020) list six challenges that need to be overcome to implement '3D data as a platform' for geospatial environments.

To make 3D data more accessible, the lack of consistency between the different models has to be solved (Stoter et al, 2020). Currently, models use different base (sensor) data, reconstruction methods, and software which leads the models to differ in geometry, appearance, and semantics. There is also no consistency regarding the format of the 3D models. The models are often stored in either XML, graphics, or binary format which also means that the underlying data model differs. However, fully solving the consistency of different models is not possible and will not be possible in the future because each model is developed for a (slightly) different purpose. When data that was placed in one model by an application, is retrieved and used by another application, the retrieved data nearly always requires manipulation or transformation as the way the initial model uses and forms the data is different from the receiving model (Bazjanac and Kiviniemi, 2007). Of course, when two cities have an influence on each other by for example bordering each other, it costs less effort to combine the two individual models of the cities with each other when both models are at least based on the same model structure.

Furthermore, according to Stoter et al (2020) standardization is needed to ensure consistency between the models. This means that geometries, as well as semantics, need to be standardized. The Open Geospatial Consortium (OGC) - an international voluntary consensus standards organization – promotes the implementation of these open standards for geographic information systems, called the OGC standard which CityGML has to adhere to.

The third challenge according to Stoter el al (2020) is the lack of data quality. Publicly available 3D city models often contain errors regarding geometry and topology, like missing surfaces, duplicated vertices, or self-intersecting volumes. These errors are often less problematic in the specific software they are modelled in but become a problem when used with other software or advanced applications, making the 3D data unusable as a platform. See Section 4.2.3 for an example regarding the lack of data quality within the datasets used for this research. A way to solve these errors according to Stoter et al (2020) is by using automatic repair algorithms or software whose 3D geometries comply with ISO 19107. A certain degree of errors should however always be expected and cannot be resolved with an algorithm especially when the data has to fit different types of models and therefore has to be structured and translated differently. León-Sánchez et al (2022) try to create an open dataset for the city of Rijssen-Holten in the Netherlands which can be used for a CityGML-based 3D city model testbed to test Urban Energy Modelling tools with. This dataset, while being rich in attributes, semantics and geometrics, the researchers proclaim that it still contains errors as "*it is impossible to create an error-free dataset*".

Stoter et al (2020) further state that designing for data interoperability is another step to make 3D data more accessible. Reaching interoperability (meaning changing a semantic 3D city model from one data format to another) is overall impossible due to incompatible semantics. Currently, for example, the conversion between an IFC model and a CityGML model is arduous because IFC has more classes than CityGML. In other words, the two models have different semantic information which are not interoperable. Another, smaller issue is that IFC BIM model needs to be georeferenced so it is spatially correctly placed in a CityGML 3D model. Pauwels (2014) further states that interoperability is a long-standing challenge and even promising strategies such as linked data technologies will not solve the interoperability challenge. While fully solving the interoperability challenge will not be possible, trying to get close to data interoperability by improving information exchange and management, is.

Often, cities, governments, and organizations do not have strategies in place to update and maintain their 3D models. Therefore, it is crucial to the long-term success of 3D models that frameworks are put in place for data maintenance and governance.

Finally, many 3D model projects are - so far - kept protected in a bubble. Translating these utopian pilots to real-world use cases presents a challenge in itself. According to Stoter et al (2020), in the real world, the 3D models have to cover a much greater area which requires automation. This makes it more difficult to monitor and control the quality of the data. However, a high-quality 3D city model or the lack thereof – including up-to-date geometric, graphic, and semantic 3D data and a validated schema - is necessary to facilitate a wide variety of urban applications which creates a dilemma.

2.3.1.3 3D urban model formats

No single and unique schema exists to store 3D city models because of the content diversity of the 3D city models. 3D city models can be stored using file-based and database approaches, the latter one being the more sophisticated choice as it allows for better data transformation, data security, and data integration as well as minimizing data inconsistency. Using a Database Management System, the data can be retrieved from the database by using multiple SQL queries and relational algebra which is not possible for file-based systems. File-based models are likely to lead to data redundance, outdated data, data inconsistency, or difficulty of accessing the data and they often require a multitude of files instead of just having one database in which all the required information is included.

To be able to develop a database model, access to the required databases needs to be granted which is not the case for this thesis. Therefore, a partially file-based model is the solution to the accessibility problem. These files need to be able to store semantic expressions to include additional information on the built environment as the files are the source of data which is then imported into a 3D database.

There are a small variety of data formats that are used to store and visualize geometrical and graphical 3D urban models and even fewer that also store semantic information on the built environment. Jie et al (2019) compare the performance of common 3D model formats.

Table 1. Performance comparison of common 3D model formats based on Jie et al (2019).

Model format	Geometry	Topology	Texture	Semantic	Geographic coordinates	LOD	Extensibility	Apply
X3D	+	*	++	/	+	+	+	*
KML	+	/	++	/	*	*	+	*
COLLADA	*	*	*	/	/	+	++	*
Shape	*	/	/	/	+	/	/	*
CityGML	+	+	+	++	++	++	++	++
IndoorGML	+	+	/	++	++	*	*	++
IFC	++	+	*	++	*	*	*	++

*for simple support, + for medium support, ++ for full support, / for no support.

Table 1 shows that the 3D model formats X3D, KML, COLLADA, and Shape all do not support semantic expressions. Data formats that Jie et al (2019) do not list, which are purely geometrical/graphical in nature but do not have sufficient semantics to answer the research question are among others VRML (a deprecated data format) (Gröger & Plümer, 2012) and .3DS (a commercial data format used by Autodesk 3DS Max for 3D modelling). Wavefront OBJ - an object file - is an open data format for 3D graphics. It only contains the 3D geometry of the building models and is suitable for 3D graphic applications or 3D CAD applications. Some other data formats that can be found in the literature but which only represent the built environment in 2D are GeoTIFF and GeoJSON (file- and exchange formats for 2D raster-based GIS data) and AutoCAD DXF (2D vector-based GIS data). GPKG (GeoPackage) is an open geodata format based on SQLite which can be used in QGIS, ArcGIS, and FME. In comparison to the other data formats that have been named so far, GPKG does contain semantic data on the built environment, however, the data format does not contain any geometries that are needed to virtually represent the built environment.

According to Jie et al (2019), the remaining common 3D model formats that do support semantic expressions are CityGML, IndoorGML, and IFC. IndoorGML was specifically designed for the representation of the indoor environment, making the data format ineffectual for the purpose of this thesis. Furthermore, IFC - which is widely used in the building industry – can have a highly detailed representation of the built environment and highly detailed semantic expressions, however, the format has poor extensibility, and is - because of its high level of detail - predominantly used on an individual building level. Furthermore, 3D city models use boundary representations while BIM (IFC) uses solid modelling (see Figure 11). This is one of the reasons why the potential integration of BIM and GIS would be difficult as the geometries need to be transformed.

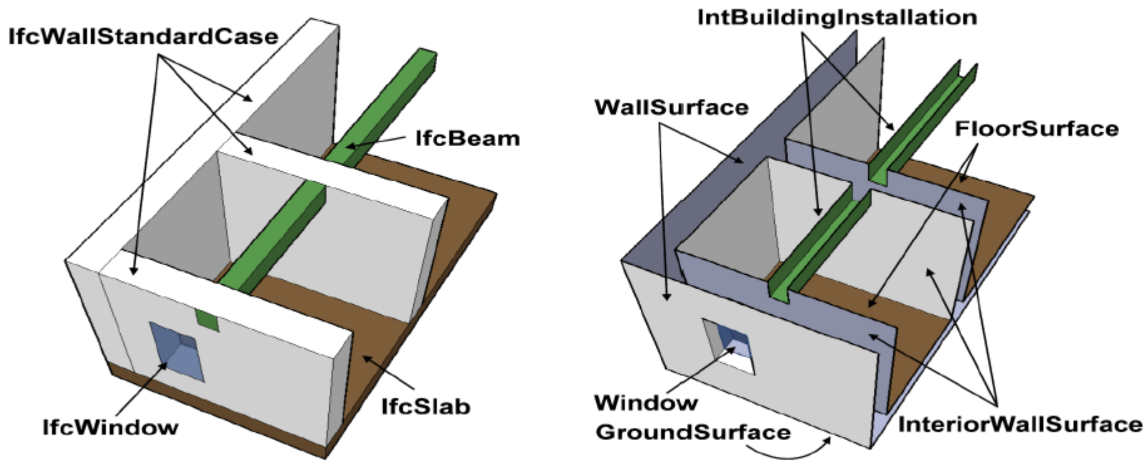


Figure 11. Differences between geometry representations in BIM and 3D GIS (Nagel et al, 2009).

Of the three, CityGML is the best alternative for storing, sharing, and in-depth application of large-scale 3D urban models according to Löwner et al (2012). Another 3D urban model format that supports semantic expressions and is overall similar to CityGML, is CityJSON.

2.3.1.4 CityGML data model

CityGML is an open data model that represents semantic 3D models of the built environment. It was initiated in 2002 by the 'Special Interest Group 3D' and first released and accepted by the OGC standard in 2008. Since 2021, the 3rd version of CityGML is available. The OGC standard CityGML is the main standard to store and exchange 3D semantic city models. To ensure interoperability between the models, CityGML -among others - makes use of ISO19107 to standardize the geometric representation of the 3D objects. For appearance purposes, textures and colours can be added to these 3D objects.

The information model does not only represent buildings but also other feature classes such as land use, bridges, transportation (like roads and railways) tunnels, city furniture, bodies of water, and plant coverage. Figure 12 depicts the module overview of the three different CityGML versions that have been released so far, each one building upon the former one.

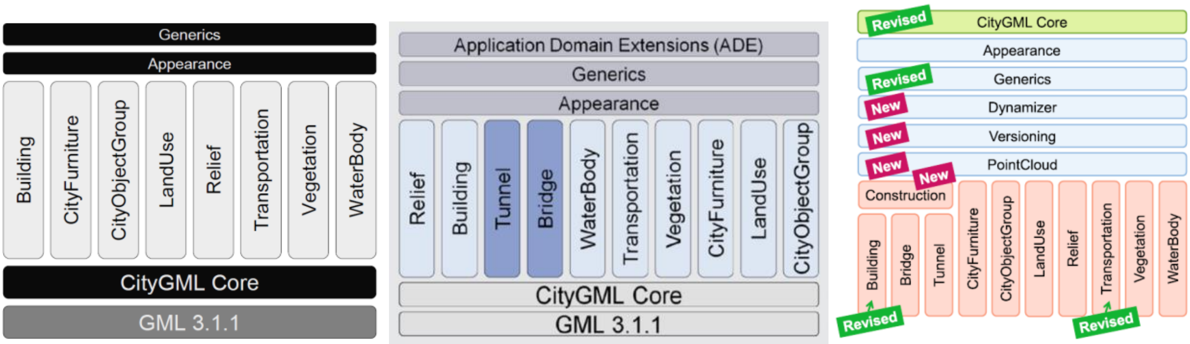


Figure 12. Module overview CityGML 1.0 (Kolbe, 2009)(left), CityGML 2.0 (Löwner et al, 2012)(middle), and CityGML 3.0 (Kutzner et al, 2020)(right).

At the core of the open data model lies a UML (Unified Modelling Language) model, a modelling language used by software engineers to provide a standard way to visualize the design of a system. Figures 13 and 14 show the visual representation of a road (*TransportationComplex*) which is the aggregation of *TrafficAreas* and *AuxiliaryTrafficAreas* in CityGML 1.0 with the corresponding UML diagram of the transportation model, respectively. Figure 15 shows an overview of the core module for CityGML 3.0.

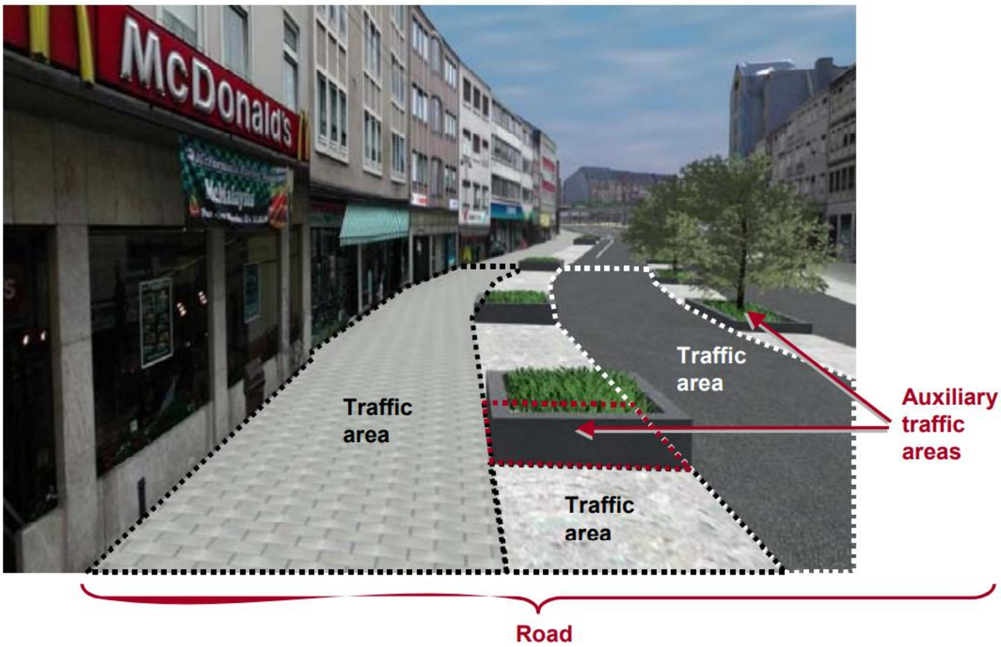


Figure 13. Example of a visual representation for a 'TransportationComplex' in LOD2 in CityGML 1.0: a road that is the aggregation of 'TrafficAreas' and 'AuxiliaryTrafficAreas' (Gröger et al, 2006).

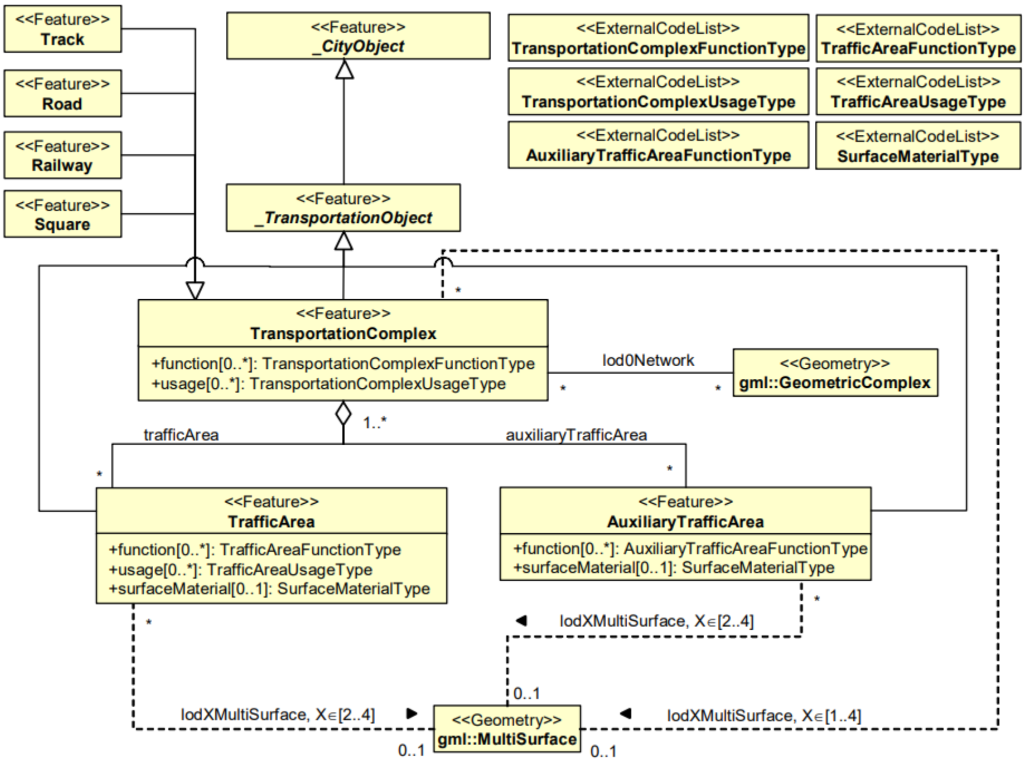


Figure 14. UML diagram of the transportation model in CityGML 1.0 (Gröger et al, 2006).

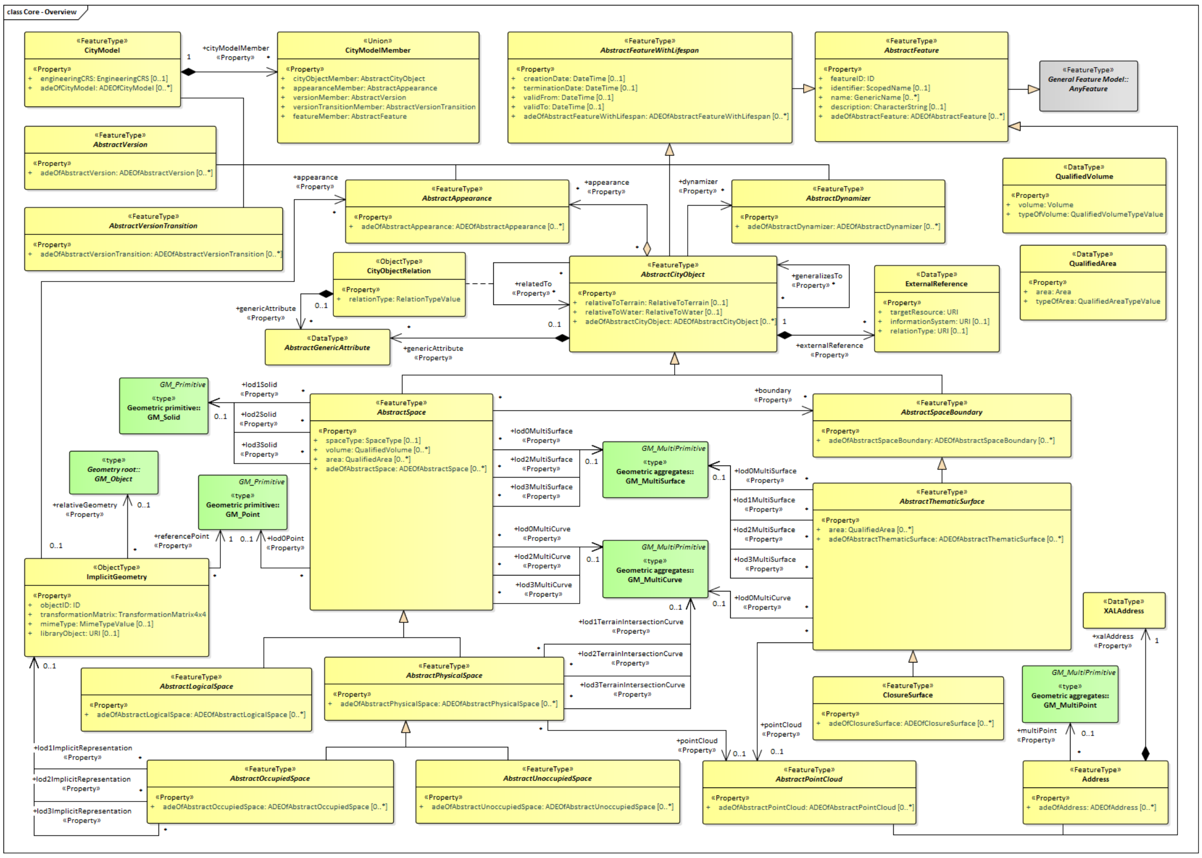


Figure 15. Overview of the UML model for the core of CityGML 3.0 (OGC, 2021) (see Appendix A for a larger representation of the UML model.

CityGML data models can also be extended into other domains by defining application domain extensions (ADEs). The most well-known and implemented ADE is used to calculate the energy demand of buildings (Gröger & Plümer, 2012; Kaden & Kolbe, 2013; Ruohomäki et al, 2018; Wate and Coors, 2015; Yao et al, 2018).

2.3.1.5 Encodings for the CityGML data model

To be able to utilize and exchange the CityGML data model, the information has to be written down in a certain way to, for example, a file. This process is called encoding. So far, three encodings for the CityGML data model exist; the xml-based encoding called CityGML, the encoding CityJSON, and the database schema 3DCityDB (Arroyo Ohori et al, 2022).

CityGML-XML

The most common and most widely accepted encoding of the model is called CityGML, not to be confused with the data model CityGML. Because of this inevitable confusion, Arroyo Ohori et al (2022) use the connotation CityGML for the data model and CityGML-XML for the xml-based encoding. For reasons of clarity, this section of the thesis will adhere to these distinctions. The rules that the XML document has to follow are encoded in an XSD file. Furthermore, CityGML files are deeply nested which makes them highly complex. On top of that, there is no standard on how to structure a file, so most files are structured slightly differently from each other. Interestingly, Gröger and Plümer (2012) state that many companies and applications are using CityGML, however, Stoter et al (2020) claim that very few software packages support XML-encoded CityGML files because of the large number of ways that features can be labelled.

The municipality of Rotterdam is one of the parties that makes use of CityGML because, according to them, CityGML has rich semantics compared to 3D graphics and 3D map formats. The objects in the data model know what they are and where they are which makes sophisticated queries, simulations, and analyses possible (Hermans-van Ree, 2018).

While CityGML-XML is the one encoding of the possible three that is most frequently used by parties, researchers from the Delft University of Technology believe that too little time was spent on deriving a usable exchange format for the CityGML data model. According to Arroyo Ohori et al (2022), *"the XML encoding is verbose, hierarchical, complex, and not adapted for the web"* which are reasons for *"the low number of software packages supporting full read/write/edit capabilities for CityGML files"* and *"the relatively low number of datasets stored in CityGML files"*. Overall, it is difficult to parse and extract information from CityGML files due to several reasons. For one, there are several different ways to store the same geometry. The blog post 'GML madness' (Rouault, 2014) explores the complexity of CityGML-XML by describing 25 different ways to store a simple square in CityGML. Developing a parser for CityGML means that all 25 ways (and more if the geometries become more complex) have to be supported. XML also requires special libraries to handle the data which creates complications. Lastly, the deep hierarchies of CityGML files also make parsing and extracting information more difficult.

CityJSON

As a replacement for the XML serialization of CityGML, researchers from the Delft University of Technology developed the JSON-based encoder CityJSON for CityGML 3.0. Just like CityGML-XML, CityJSON is an OGC standard compliant with CityGML 2.0 but also supports up to 90% of the features of CityGML 3.0. The 'missing' 10% of the features were omitted on purpose according to Arroyo Ohori et al (2022) to keep CityJSON 'lean' and easy to use. The features that were kept, have the same names as the CityGML classes. However, the original deep hierarchy is flattened out and divided into 2 levels; 1st-level city objects and 2nd-level city objects (Arroyo Ohori et al 2022). Figure 16 depicts the implementation of the CityJSON classes. The 'flattening out' of city objects is one of the reasons which makes it easier for developers to read, process, and write new CityJSON files compared to new CityGML files. Yet, this will likely make it more difficult to (de)serialize in a few other programming languages. CityJSON files are also easier to exchange because of their smaller file size. Compact CityJSON files have - on average – a compression factor of around 6 with real-world datasets (Ledoux et al, 2019). Reducing the file size also increases the time performance of the 3D city model, especially for large-scale urban models with a great amount of semantic information (Liempt, 2020).

One main characteristic of CityJSON is that it was developed in such a way that programmers can easily add supporting tools and APIs (Ledoux et al, 2019; Stoter et al, 2020). Nowadays, several software packages are in development that support CityJSON. One of these software is a conversion tool that can convert CityGML files to CityJSON files and vice versa widening the application potential of CityJSON. However, most of the software that does support CityJSON, are tools that were developed by the Geomatics department of TU Delft or (former) members of the department. 3D BAG is one such tool. It is the first open, downloadable, and fully automatically generated 3D building data set covering all of the Netherlands. One of the only software that supports CityJSON but that does not originate from the TU Delft is 3DCityDB.

To note, the research exploring CityJSON has remained within the TU Delft with there being no noteworthy papers on the subject from other researchers so far.

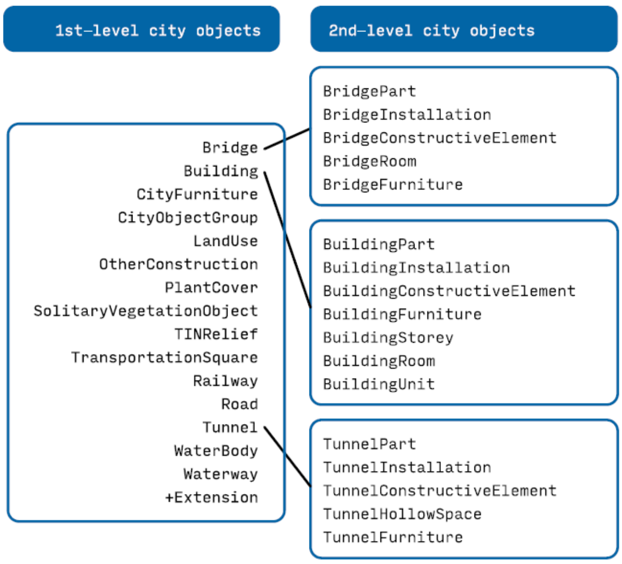


Figure 16. The implementation of CityJSON classes into 1st and 2nd levels (Arroyo Ohori et al, 2022).

3DCityDB / Database schema

Another way to encode the CityGML data model is by means of the database schema '3DCityDB' ('3D City Database') which is an open-source geo-database for PostgreSQL/PostGIS and Oracle Spatial. Several municipalities around the world such as Berlin, Potsdam, Frankfurt, Vienna, Salzburg, Singapore, Helsinki, Zürich, Rotterdam, and the Hague adopted 3DCityDB to manage their 3D city models (Arroyo Ohori et al, 2022; Jie et al, 2019). The database stores CityGML data models in a relational database and contains *"a set of database procedures and software tools allowing to import, manage, analyse, visualize, and export virtual 3D city models according to the CityGML standard"* (Yao et al, 2018).

2.3.1.6 LODs

Semantic 3D urban models reduce the complexity of the real world so that the model can be stored and used for analyses without requiring huge amounts of computer power. By reducing the complexity, visualizations and analyses become more smooth and efficient. Depending on the spatial analyses and the visualization required to answer a spatial question, a certain level of detail of the semantic 3D urban model is required. The highest level of detail is not always required for research and therefore striving for a perfectly detailed representation of the built environment is not particularly encouraged. By overlapping geometries with aerial images, users can still 'see' a more detailed environment while the rendering and processing capacity is kept low. Due to these nuances, different levels of detail (LODs) are defined to communicate how thoroughly the features were acquired and modelled and the semantic expressions they should include (Luebke et al, 2003). Of all the 3D GIS data standards, CityGML has the most complete definition of LODs. The five levels of detail of CityGML were distinguished by the Open Geospatial Consortium (2012) for CityGML version 2.0; LOD0, LOD1, LOD2, LOD3, and LOD4 (see Figure 17).

- LOD0 represents the building footprint,
- LOD1 corresponds to the extrusion of the building's footprint to its maximum building height,
- LOD2 depicts the rough outline of a house including its ancillary structure and roof structure,
- LOD3 illustrates the detailed appearance of a building including doors, windows, chimneys, balconies, etc,
- And lastly, LOD4 also displays the outer appearance of LOD3 but additionally adds the internal structure of the building including rooms, stairs, furniture, and interior semantics.

Figure 17. The five official LODs of a building in CityGML 2.0 (Open Geospatial Consortium, 2012).

But the LODs do not only set a framework for the geometric representation of an object but also define the minimum semantic information required per level. While LOD0 does not have to provide any semantic information, LOD1 has to at least include the height of the building. Models in LOD2 should contain information on the different roof shapes, walls, and floors while models in LOD3 should additionally include information on roof overhangs, doors, windows, and wall details. The last LOD4 should contain the same information as any of the levels below but additionally include semantic information on rooms and furniture. Table 2 lists an overview of the characteristics and applications of the 5 LODs for CityGML 2.0 including their modelling methods, semantic information, and potential applications.

Table 2. The characteristics and applications of 5 LODs for CityGML 2.0 based on Jie et al (2019).

LOD hierarchy	Modelling methods	Semantic information	Potential applications
LOD1	2D vector stretching, point cloud processing	Building height	3D maps, environmental noise simulation, viewable area analysis, shadow analysis, population estimation
LOD2	Photogrammetry, airborne laser point clouds	Different roof shapes, walls, floors	Rooftop solar energy estimates, building energy demand estimates, urban energy planning
LOD3	Ground laser scanning, BIM model conversion	Roof overhangs, doors, windows, wall details	Simulation of energy consumption
LOD4	BIM model conversion	Room, furniture	Integrated indoor and outdoor space analysis, facility management, indoor navigation, emergency response, cultural heritage protection, disaster management, flood and inundation analysis

In 2014, before there was a consensus on the level of detail in 3D city modelling, Biljecki et al proposed a formal and consistent framework that defined 10 discrete LODs. Later on, the amount of LODs was reduced to 5 and officially introduced as an OGC standard. Despite the general acceptance of this new definition of LODs, Biljecki et al (2016) argue that the 5 LODs are too generic and insufficient from a geometrical point of view and that their precise specification of each other is lacking. Therefore, Biljecki et al (2016) have proposed a refined definition of 16 LODs that build upon and supplement the LOD of CityGML 2.0 and provide a stricter specification regarding the exterior geometry of buildings which allows less modelling freedom and ensures greater similarity between models and diminishes the potential misunderstanding between stakeholders and potential errors. The refined LOD specifications by Biljecki et al (2016) for 3D building models in CityGML 2.0 are depicted in Figure 18.

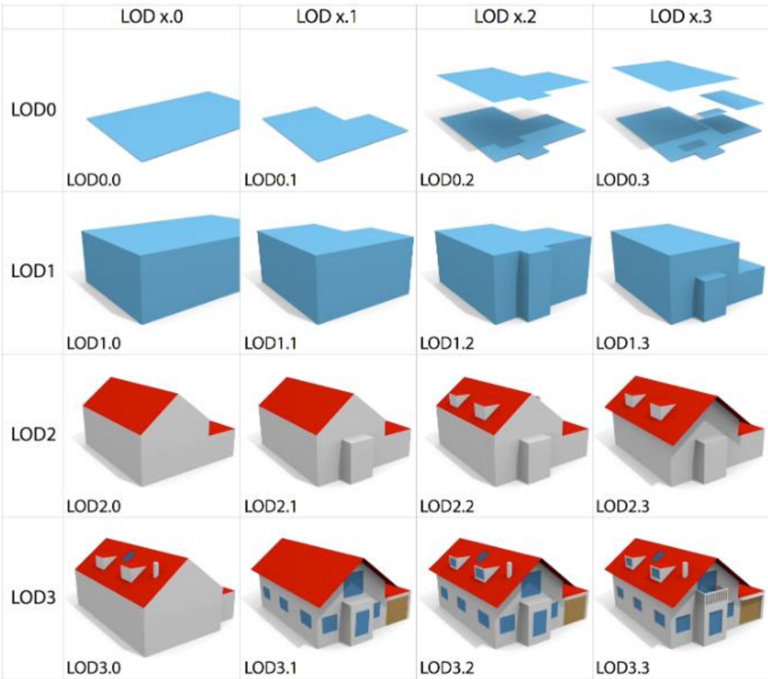


Figure 18. Refined LOD specification for 3D building models by Biljecki et al (2016).

While the LOD concept was revised for CityGML 3.0, the framework by Biljecki et al (2016) was not (yet) accepted by the OGC standard for CityGML 3.0. However, for the new CityGML version, LOD4 which represented the interior of objects in CityGML 2.0 was removed as Biljecki et al had intended in their proposed framework (Kutzner et al, 2020).

2.3.1.7 Examples of projects developing 3D city models

The number of cities that are working on building some sort of 'Digital Twin' of themselves is increasing. Cities such as Amsterdam, Utrecht, Rotterdam, Zürich, Helsinki, Stockholm, Herrenberg (Germany), Amaravati (India), Singapore, and Jakarta have all been developing an Urban Digital Twin of some kind. Figures 19 to 23 show a variety of already existing 3D city models of cities.

The city of Zürich for example uses its 3D urban model among others to conduct solar potential analyses, model noise, and air pollution as well as mobile phone radiation, and visualize the impact of new construction projects on the surrounding area and the future development of high-rise buildings (Schrotter & Hürzeler, 2020). Meanwhile, Helsinki - one of the cities that has been working on developing a digital twin for the longest - developed a model that is accessible to the public through its urban platform and open data catalogue. The open urban digital twin is meant to stimulate inhabitants to explore their building's energy performance compared to the rest of the city, as well as their roof's heat loss, 'green roof' potential, and solar power potential (Ruohomäki et al, 2018).

Berlin started developing their spatial and semantic 3D city model in 2003 and since 2015 it is freely available to the public. The municipality of Berlin not only uses the model for 3D visualizations but also for urban planning, urban energy demand estimation of each individual building in the city (including heating, electricity, and warm water energy), and environmental noise simulations (Jie et al, 2019; Kaden & Kolbe, 2013).

One of the most sophisticated 3D city models in existence is the dynamic 3D model and collaborative platform of Singapore. The R&D program 'Virtual Singapore' was initiated by the National Research Foundation (NRF), took 5 years to complete, and cost more than $73 million. The project uses a variety of rapid mapping techniques like oblique imaging, aerial laser scanning, mobile laser scanning, and ground scanning. The Virtual Singapore Platform is able to integrate static, dynamic, and real-time urban data and information such as demographic data or climate information. Among others, the model is used for;

- urban energy consumption,
- solar energy potential and production (based on an analysis of light, shade, and temperature),
- information on the duration of direct sunlight exposure on specific windows,
- water disposal,
- community navigation (communicate initiatives to residents in real-time, 'smart walking'),
- crowd movement simulation in a shopping mall (simulate the duration of arrivals and exits using faster escalators or guides),
- transportation planning (autonomous vehicles use the 3D model for driverless navigation on the roads, residents can check if an autonomous vehicle is available in the area, virtual walkthroughs),
- disaster management (simulate gas leaks and prepare first responders and residents accordingly),
- and disease transmission (Jie et al, 2019; National Research Foundation Singapore, n.d.).

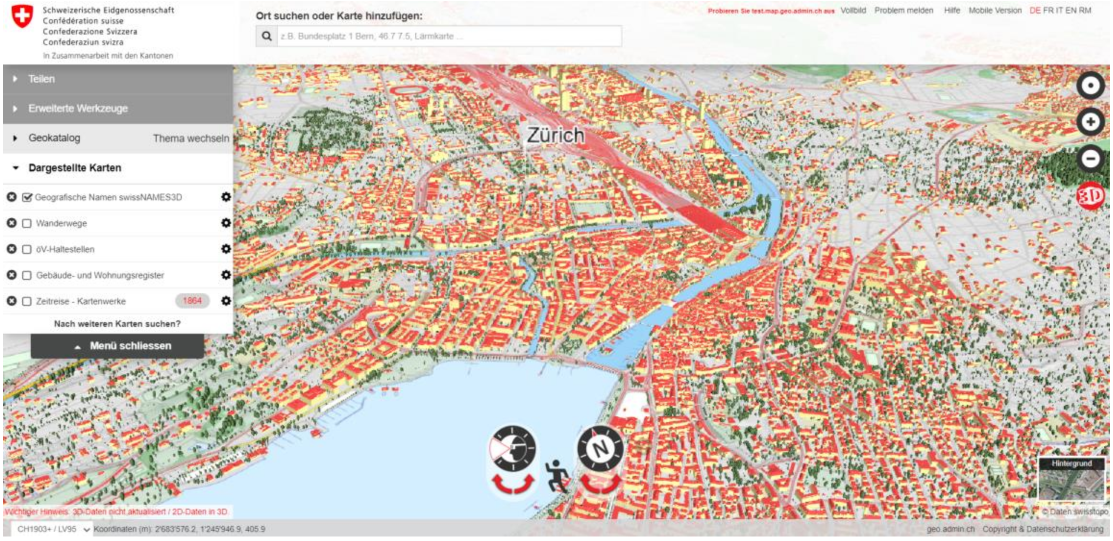


Figure 19. Semantic 3D model of Zürich (Schweizerische Eidgenossenschaft, n.d.).

Figure 20. Another semantic 3D model of Zürich (Stadt Zürich, n.d.).

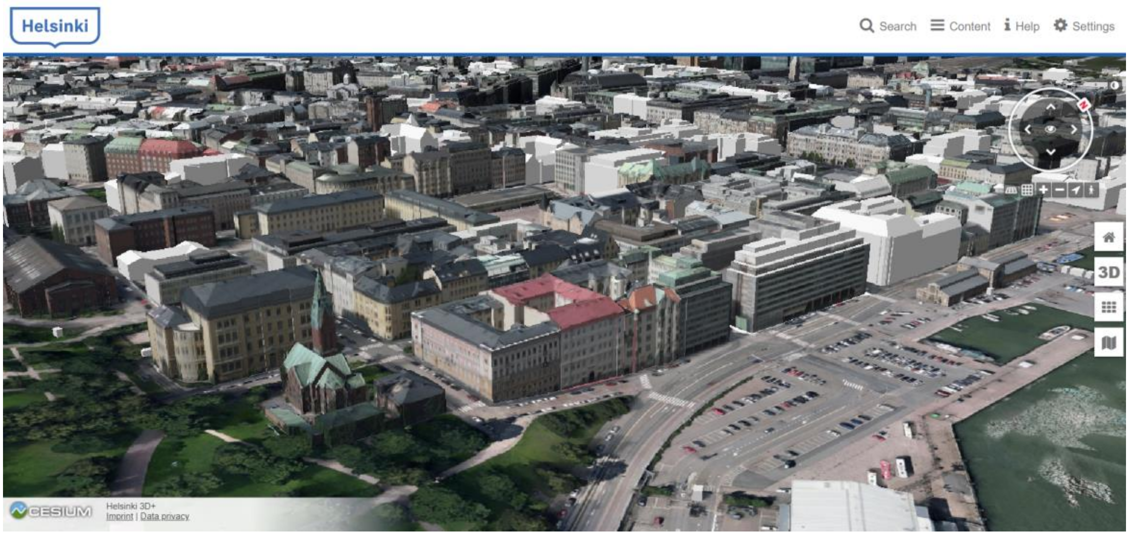


Figure 21. Semantic 3D model of Helsinki (City of Helsinki, n.d.).

Figure 22. Semantic 3D model of Berlin (Berlin Partner for Business and Technology, 2022).

Figure 23. Dynamic and semantic 3D city model and collaborative platform of Singapore (National Research Foundation Singapore, n.d.).

Another example of a digital twin is the demo version of Antwerp. Here, a 3D city model was created that visualizes the effect of a road closure or a heavy storm on the traffic flow, air quality, and flood risk in the city over time. So far, models that include a time element - which makes a 3D model among others an urban digital twin – are scarce which makes the model of Antwerp quite unique. However, until now, the model can only run two specific scenarios and is therefore only a demo version. Figure 24 visualizes the effect of a closed road in the centre of Antwerp on the traffic flow/jam during morning rush hour (9 am).

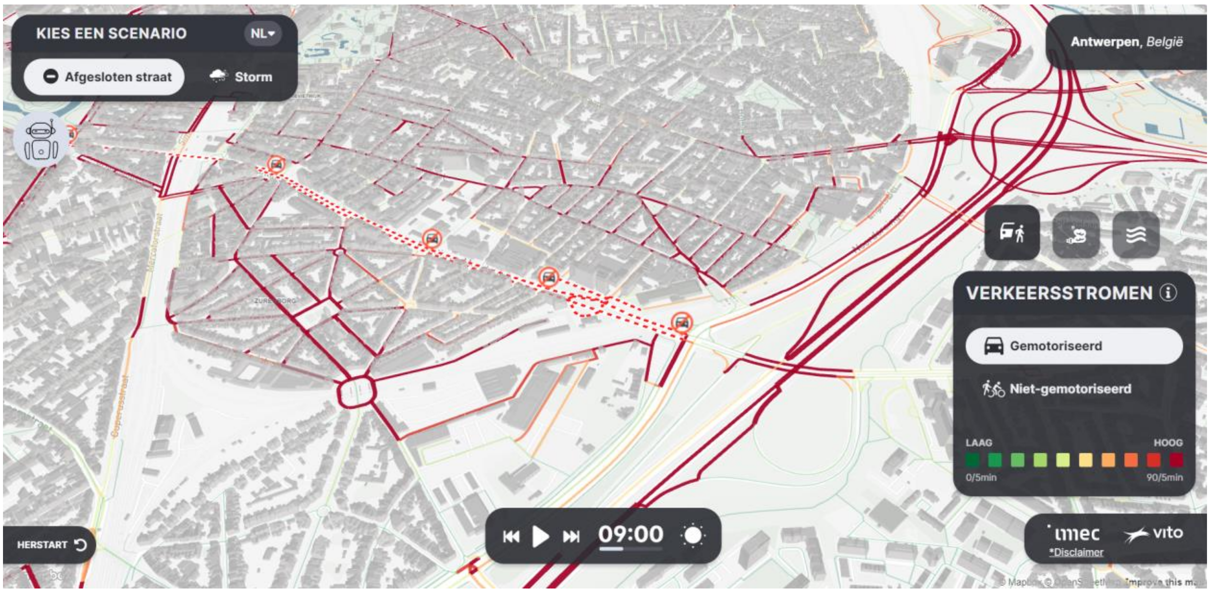


Figure 24. Digital twin demo of Antwerp (IMEC, 2018).

Besides municipalities and companies who are working towards developing data-enriched 3D models of cities, there are also institutions that are working towards developing 3D city models of countries. The geoinformation research group of the TU Delft for example developed 3D BAG, the first open 3D building data set that covers all of the Netherlands and which is generated fully automatically by using building data from the BAG (Register of Building and Addresses) and the height data from the AHN (National Height Model of the Netherlands).

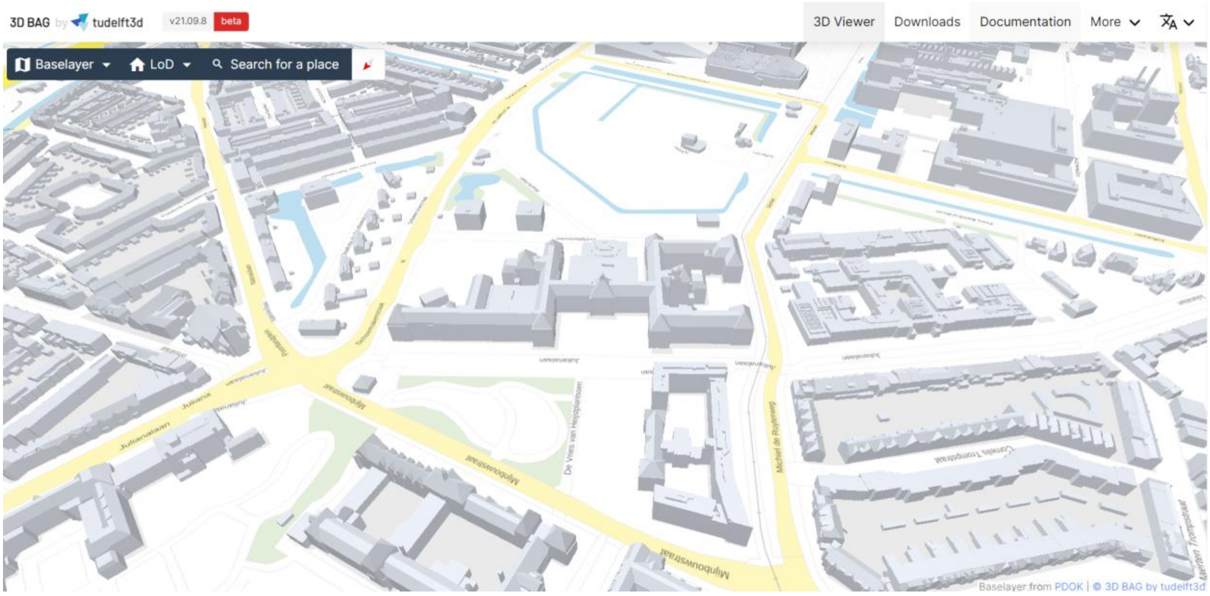


Figure 25. 3D BAG viewer (Tudelft3d, n.d.).

At the same time, the United Kingdom's Digital Twin programme is developing an ambitious 2D digital twin of the UK which is meant to assess the impact of climate change - and currently in particular flooding – on the country's energy-, water-, and telecom network. CReDo (Climate Resilience Demonstrator), the digital twin, is supposed to model the interdependencies between infrastructures to assess the effect of a flood on a city and even on the whole country. At the moment, CReDo is still in the demonstration phase and far from being implementable on a country-wide scale. However, the system architecture of CReDo gives a good insight into what is needed to develop a digital twin that can be used to evaluate the effect of flooding on all infrastructure networks (see Figure 26), even though only a 2D model instead of a 3D model is being used.

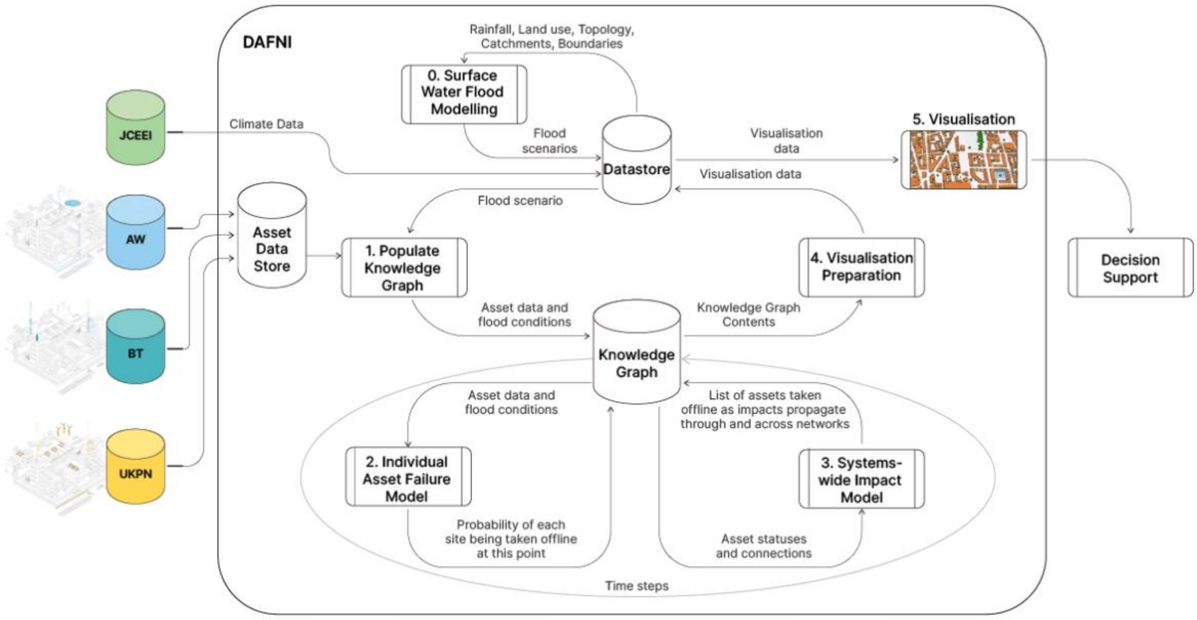


Figure 26. System architecture of CReDo (National Digital Twin Programme, 2022).

2.3.2 City planners and the application options for semantic 3D city models

So far, city planners only sporadically use semantic 3D city models as spatial decision tools. The lack of integrated and user-friendly software for dealing with 3D city models is probably one of the reasons for this. While the application potential and variety is great, as the former section has shown, the actual integration of the spatial application into the process of urban planning is more difficult and still requires – due to the current lack of ready-to-use tools available on the market - some form of programming and computing skills which most city planners do not have. Stoter et al (2020) support this claim by stating that city planning and environmental simulations are fields where the availability and application of 3D models still have room to grow. Currently, many municipalities only use their semantic 3D city model for visualization purposes whereas the models have the potential to be used for a wide range of purposes including energy and noise studies as well as design-related studies such as line of sight- and shadow analysis, clash detection of cables and pipes in the underground, and the impact of wind circulation like García-Sánchez (2017) has shown in her research and can be seen in Figure 27. León-Sánchez et al (2022) in the meantime developed a rich open dataset for the municipality of Rijssen-Holten in the Netherlands that functions as a CityGML-based 3D city model testbed to test Urban Energy modelling tools on.

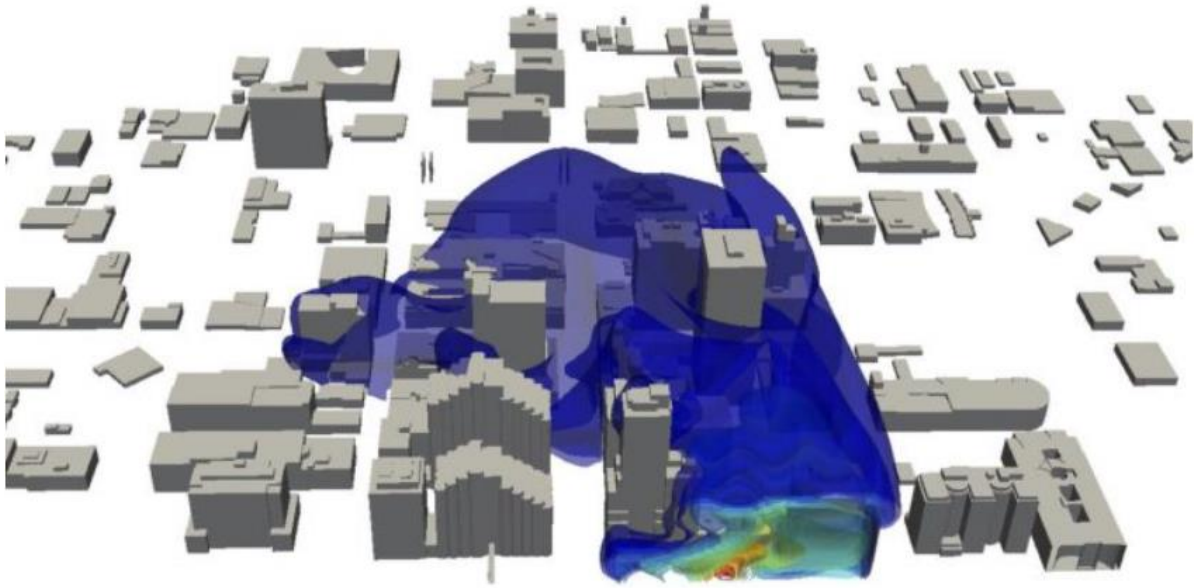


Figure 27. Wind circulation in a 3D city model (García-Sánchez, 2017).

In combination with a flood simulation model (see Section 2.2), semantic 3D city models have the potential to uncover the direct and indirect effects of a flood, helping municipalities and city planners to avoid, mitigate, and manage major flood events and design flood resilient cities in the process. Therefore, this thesis will test if it is possible to develop a semantic 3D city flood model that can evaluate what kind of far-reaching effect a flood has on a city and its critical infrastructure points and if it is possible to evaluate the flood resilience of new design plans beforehand.

2.4 Conclusion

According to the 2020 Global Risk Report by the World Economic Forum (2020), three of the top five risks that the world is currently facing - by both likelihood and impact - are related to climate. Among extreme weather events, flooding is seen as one of the major contributors to loss of human life and economic damage. The UN environment programme (2020), furthermore, states that floods are going to become more frequent in the near future due to long-term global climate change making floods an even more serious threat. Urban areas are especially vulnerable to floods due to their high population and infrastructure density. At the same time, urbanization is changing the hydrological status of urban areas and the flow path of the water by building new roads and buildings and destroying a city's natural flood defence system such as the water infiltration rate of soil in the process (World Economic Forum, 2019; Yang & Zhang, 2011; Zhi et al, 2020). Furthermore, during an urban flood, critical infrastructure such as road network, electricity network, mobile network, and public health networks play an important role in either preventing or mitigating the extreme environmental hazard or accelerating the disaster even further.

Building flood resilient cities is therefore becoming increasingly important to mitigate more extreme urban hazards, withstand the increased threats and recover from incidents more quickly.

Quantifying and assessing the impact of an urban flood to draw a conclusion on the flood resilience of a city is not a straight forward method (Hammond et al, 2015). Researches conducted so far have in common that they all produce some kind of flood resilience score. What the researches do not do, is to get an overview of the effect that a flood has on a city to establish the resilience of a city. Flood models are yet incapable of identifying the direct as well as indirect effects of a flood on a city's infrastructure and its inhabitants as they are missing important information on the urban environment itself that goes beyond the geometries and infiltration rates used for flood simulation models. By connecting a flood model to a semantic 3D city model which is capable of handling a great amount of urban data, the flood resilience of a city could be identified.

Semantic 3D city models are a promising, newly emerging type of data-driven base model to conduct complex urban analyses with. In essence, a basic 3D city model is a digital representation of the built environment. However, semantic 3D city models go beyond visualizing the built environment as they have the potential to become integrated information models that can be used for many different urban spatial analyses. The variety of 3D urban models and the lack of unified modelling and coding standards have been leading to 3D models being created in different data formats (Stoter et al, 2020). Of all the available file-based 3D model data formats CityGML is the best alternative for storing, sharing, and in-depth application of large-scale 3D urban models according to Löwner et al (2012). At its core, CityGML is an open data model that represents semantic 3D models of the built environment. So far, there are three encodings for the CityGML data model; the xml-based encoding called CityGML, the encoding CityJSON, and the database schema 3DCityDB.

Currently, the interest in and application potential of semantic 3D city models is great. But while municipalities are developing their own 3D city models, they often do not fully exploit the potential of these models but only use the models for visualization purposes. These models, however, have the potential to be used for a wide range of purposes including energy and noise studies as well as design-related studies such as line of sight- and shadow analysis, clash detection of cables and pipes in the underground, and the impact of wind circulation like García-Sánchez (2017) has shown in her research. In combination with a flood simulation model, semantic 3D city models have the potential to uncover the direct and indirect effects of a flood, helping municipalities and city planners to avoid, mitigate, and manage major flood events and design flood resilient cities in the process.

Therefore, this thesis will test if it is possible to develop a semantic 3D city flood model that can evaluate what kind of far-reaching effect a flood has on a city and its critical infrastructure points and if it is possible to evaluate the flood resilience of new design plans beforehand.

3. Research approach

The following research follows the design and engineering research cycle aimed at developing a method to support urban planners in evaluating flood resilience through a semantic 3D city model using only open-source data and tools with the exception of the software FME which was accessed using a free student license. During the process, the research design problem is investigated, real data is collected from the municipality of Rotterdam, and the method is developed and validated. Only for the spatial planning decision tool some simulated data was created.

This chapter starts with an overview of the research design (Section 3.1) divided by its three phases, followed by an insight into the chosen study area (Section 3.2), information on how the data used during this research was managed (Section 3.3) including the collection of the data (Section 3.3.1) and the software that was used throughout the process (Section 3.3.2). Lastly, limitations facing this research are discussed (Section 3.4) and a conclusion is drawn (Section 3.5).

3.1 Research design

The graduation thesis is divided into 3 parts with part 1 being the most elaborate and having 3 phases and parts 2 and 3 both having 1 phase. Phase 0 including sub-questions 1, 2, and 3, establishes the theoretical framework of the research, while phases 1.1 to 3 and their corresponding sub-questions form the practical part of the research. The first part starts off with a theoretical framework including a literature review that builds the academic foundation for the whole research. The remaining phases in part 1 as well as parts 2 and 3 follow the same structure, namely first a development phase followed by the validation and output of the development. Finally, the results of the main research question and the sub-questions are evaluated and a conclusion is drawn followed by a discussion. The visual representation of the structure of the research is depicted in Figure 28.

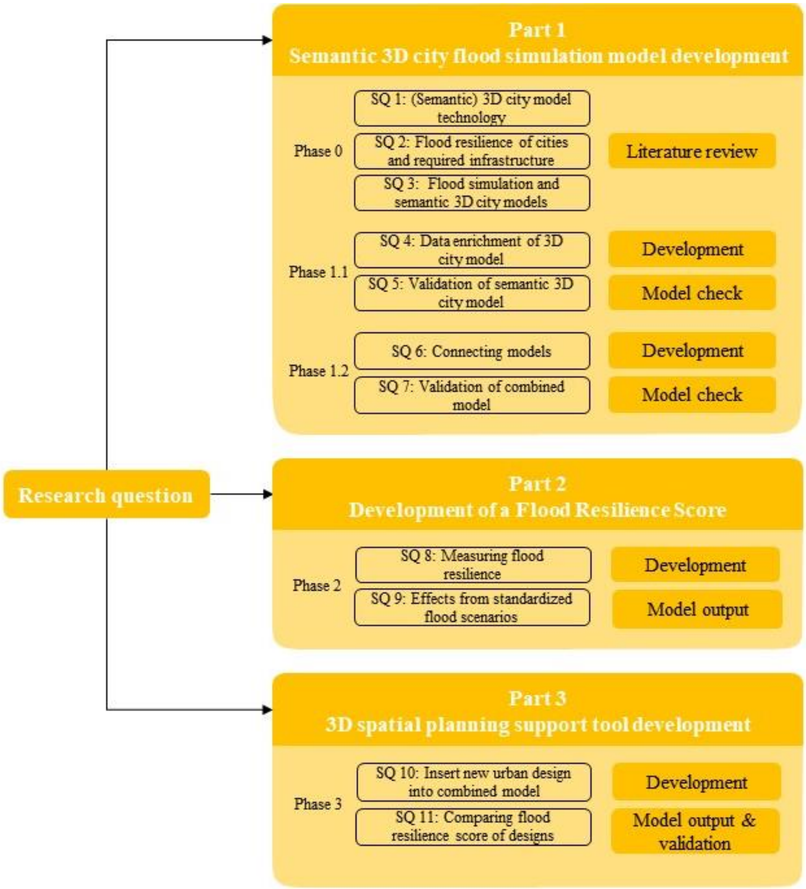


Figure 28. Structure of research.

The following subsections explain the research approach per phase. Figure 29 depicts a schematic representation of the whole research design.

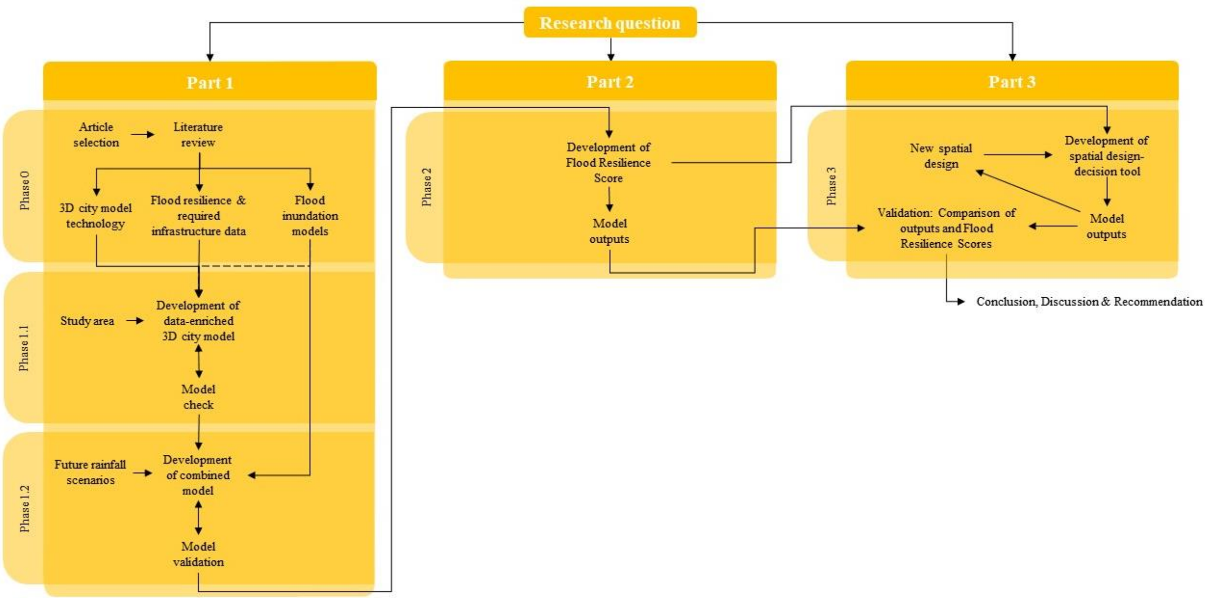


Figure 29. Schematic representation of the research design.

3.1.1 Phase 0 – Literature review

During the first phase of the research, a literature review is conducted in Chapter 2 to answer sub-questions 1, 2, and 3. The research starts by answering the question; how can the emerging technology of semantic 3D city models be used to evaluate and design the flood-resilient cities of the future and which 3D city model formats can be used to answer the research question? Potential 3D city models and their formats and input and output requirement are explored as well as the required Level of Detail (LOD) to get accurate results. The research then continues by giving insight into what flood resilience is and which urban data is needed to measure the flood resilience of a city. Next, the state of the art of flood inundation models, their suitability to evaluate urban floods, and the possibility of using the results from a flood simulation model as input for a semantic 3D city model to get a more detailed insight into a flood's impact on a city, are discussed.

3.1.2 Phase 1.1 – Development of semantic 3D city model

Based on the insights gained during the literature review, a 3D-city base model and a suitable and compatible flood simulation model are chosen. The process of choosing these models takes into account that researchers need to balance the urge to use the most realistic model with the level of detail that is actually needed because of computational demand, cost of data collection, model set-up, and requirements of the end-user (Teng et al, 2017).

For the study area, the city of Rotterdam is chosen due to its geographical location, its availability of publicly online-accessible urban data, and for its already existing 3D city model viewer which allows the user to download LOD2 urban data – in the form of buildings, bridges, and trees - in several data formats including CityGML (Gemeente Rotterdam, n.d.-a). The 3D BAG viewer by Tudelft3d (n.d.) can also be used to download the building layer of Rotterdam in CityJSON format.

Figure 30. 3D city model viewer of Rotterdam (Gemeente Rotterdam, n.d.-a).

Based on the flood resilience insights gained in phase 0, the existing 3D city model is enriched with required urban data using FME software and by setting up a connection to the BAG database using a Web Feature Service (WFS). The following information is added to develop a semantic 3D city model;

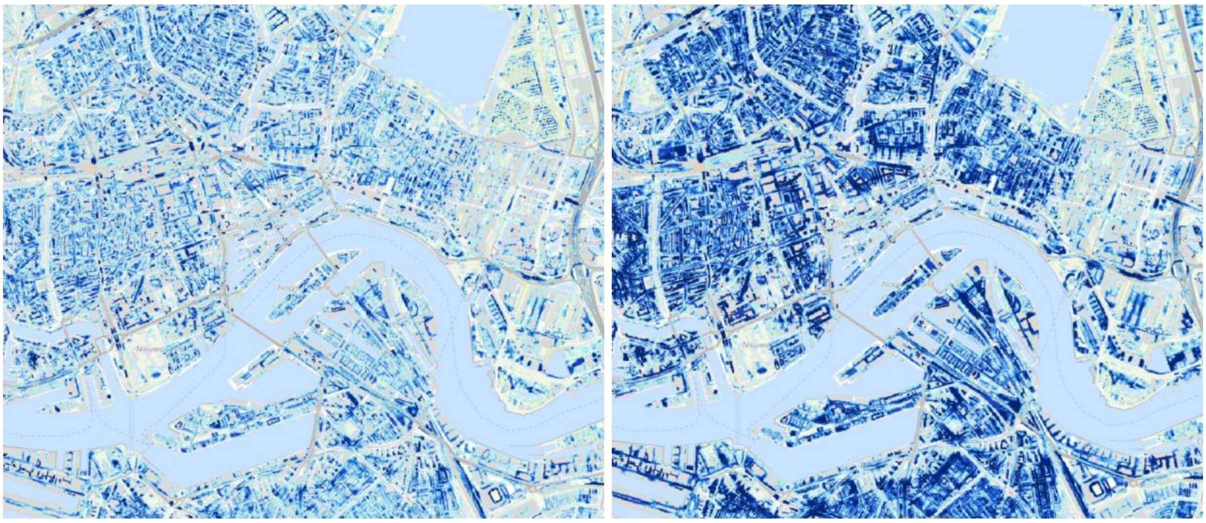
- Function(s) per building,
- Address(es) per building,
- Number of households per building,
- Neighbourhood that each building is located in,
- Vital, vulnerable, and dangerous infrastructure points,
- Trees, and
- City furniture including street lanterns, bicycle racks, and parking meters.

The data-enriched CityGML model is then inspected in the FME Inspector to validate that the model indeed includes the data that is required to evaluate a city on its flood resilience. The semantic 3D city model is then stored in 3DCityDB, one of the three possible encodings for CityGML data models described in section 2.3.1.5.

3.1.3 Phase 1.2 – Development of 3D city model and flood simulation connection

Phase 1.2 focuses on developing a connection between the 3D city model of Rotterdam - which was enriched with data in the previous phase - and a flood simulation model. The connection is created by using the output data of the chosen flood simulation model as input data for the 3D city model. This direction of the one-way connection was chosen because feeding the 3D city model data into the flood simulation model instead of the other way around, would require proprietary access to the flood simulation software. Furthermore, the computer power needed to run the data-enriched flood simulation model would steeply increase and result in lags during fluid dynamic calculation and the visualization of the flood. By feeding the 3D city model with simulation data instead of the other way around, a model is created that has the potential to give additional insight into a city's climate resilience by inserting data output from other climate-related events. Eventually, one will not want to implement the results of a simulation model into the 3D city model but actually connect the simulation model to the 3D city model. But for now this is outside of the scope of this research.

The simplified hydrodynamic simulation model 'Rainfall Overlay' by the geo-design company Tygron was chosen for this research as output data from this model is freely accessible through the Klimaateffectatlas (n.d.) thanks to Deltares. The flood model determines - per time step - the amount of rainwater from an intense rainfall that either infiltrates into the ground, ends up in the sewage system, or flows downstream and records the maximum inundation depth (Deltares, 2018). The slope and the roughness of the surface determine if water will run downhill or remain in a certain location. According to Deltares (2018), the 'Rainfall Overlay' model can quickly run the required flood simulations and determine the inundation of the floods on 2-by-2-meter grid cells while basing its simulation on public urban data. The two rainfall intensities that are used for the simulation are based on research conducted by the KNMI, the Royal Dutch Meteorological Institute (Koninklijk Nederlands Meteorologisch Instituut). The KNMI determined that, on average, every 100 years, a location will experience at least one rainfall during which 70mm of water will fall per 2 hours (see Figure 31). Every 1.000 years a rainfall of 140mm of water per 2 hours is expected (see Figure 32). Even though 1.000 years seems far away into the future, there is always a chance that this intense rainfall will occur tomorrow, so it is important for urban planners to take this situation into account as well. Note: the rainfall model by Tygron simulates a rainfall of 2 hours followed by a dry period of 4 hours so the water mass can 'settle' and during these 6 hours, the maximum inundation depth per 2x2-meter grid cell is recorded (Deltares, 2018).



Figures 31 & 32. Flood inundation map of Rotterdam resulting from a rainfall intensity of 70 millimetres (left) and 140 millimetres (right) per 2 hours (Klimaateffectatlas, n.d.).

The semantic 3D city model (stored in 3DCityDB) is 'fed' with the output data from the hydrodynamic simulation model 'Rainfall Overlay' using the QGIS plug-in '3DCityDB-Loader' which connects the free and open source geographic information system QGIS to the 3DCityDB. The plug-in - developed by the TU Delft - allows the user to easily load the 2D flood map in the form of a raster layer (TIF format) into QGIS. After converting the raster layer into a vector layer, spatial queries can be run on the flood data and the 3D model to find all flooded as well as indirectly affected objects. This method is also more user-friendly than for example trying to connect the TIF data to the 3D model using FME which makes it more accessible to urban planners who are most likely already familiar with QGIS.

At the same time, the 3DCityDB-Loader can be used to easily edit attributes of objects (but only one attribute per object at a time) and delete features which makes finding and adjusting faulty objects a lot simpler and more user-friendly. The 'delete'-function of the 3DCityDB-Loader is also a feature that will come in handy during phase 3 (see Section 3.1.5).

After the output data of the flood simulation is added to the semantic 3D city model of Rotterdam, the data of the flood is visualized to check that the semantic 3D city flood simulation was connected correctly. The interface of QGIS already does so, but only in 2D. According to Kumar et al (2018), several web-based 3D technologies can execute this task; Unity3D engine, Virtual Globes (such as Cesium, OpenWebGlobe, and WebGLEarth), and 3D Web GIS tools (NJ Flood Mapper, Sea level rise and coastal flooding impacts viewer, and Lakes entrance flood visualization tool). Figure 33 depicts the results by Kumar et al (2018) showing the visualization of a flood using Cesium.

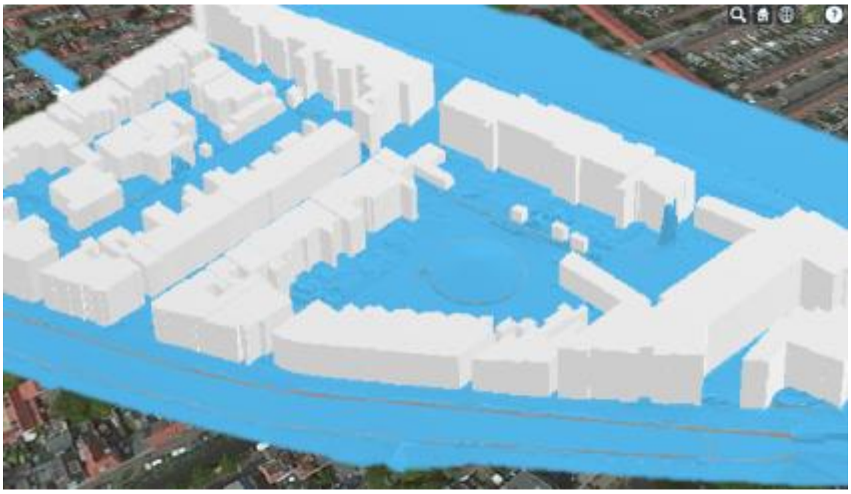


Figure 33. Cesium visualization of a flood (Kumar et al, 2018).

While these are all possible options, for this thesis, however, the Qgis2threejs plugin is chosen to visualize the semantic 3D city flood simulation as it does not require the data to be exported first and then loaded into the 3D technology.

3.1.4 Phase 2 – Development of a Flood Resilience Score

After the urban flood is added to the semantic 3D model and visualized, the flood resilience of the city is measured. As the theoretical framework has shown, measuring flood resilience in not an easy feat, but the Flood Resilience Score (FReSco) can give an overall insight into the number of buildings, households, and infrastructure points that are directly and indirectly affected by a flood. The score also allows urban planners to compare individual areas with each other or with the overall score of for example a(nother) city or even the whole country, giving an indication of which areas need the intervention of urban planners and which areas should be given priority. The Flood Resilience Score is made up of several indicators;

- *number of households directly affected* (households residing in a flooded building),
- *number of households directly and indirectly affected* (not counting the directly affected households twice when they are also indirectly affected by flooded infrastructure points),
- *number of buildings directly affected* (flooded),
- *number of buildings directly and indirectly affected* (not counting the directly affected buildings twice when they are also indirectly affected by flooded infrastructure points), and
- *number of infrastructure points disrupted* (flooded).

To be able to formulate the Flood Resilience Score, the BAG IDs of the directly and indirectly affected objects from the semantic 3D city flood simulation need to be queried. To do so, first, all the buildings that overlap the flood layer are selected and saved as a new layer followed by identifying all critical infrastructure points that are flooded. All vulnerable infrastructure points such as elderly homes and monuments are visualized and buffers are created around each vital and dangerous but flooded infrastructure point to include their 'reach' when disturbed and to be able to include the indirectly affected objects as well.

The BAG IDs of the directly and indirectly affected objects are then extracted from each corresponding QGIS layer in the form of an excel document. Then, this information is merged with additional information on the building objects (such as their address, building function, number of households per building, and their critical infrastructure point status), gathered from the semantic 3D city model stored in the 3DCityDB which is also extracted in the form of an excel document. Merging the files using Excel's Power Query then leads to an overall excel document listing the information of each building in the study area and its status (flooded, affected by the flood, or within reach of a dangerous infrastructure point). At the same time this document can be used to extract information on the overall amount of households in the study area, the number of households directly and indirectly affected, as well as the total number of critical infrastructure points and the number of flooded infrastructure points.

The Flood Resilience Score divides the directly (and indirectly) affected buildings/households/infrastructures by the total number of directly (and indirectly) affected buildings/households/infrastructures within the study area. The score varies from 0% to 100% where 0% means that the study area has no flood resilience at all whereas 100% indicates great flood resilience.

$$FReSco_a = 100 - \frac{100 * X_{f,a}}{X_a}$$

$FReSco_a$: Flood Resilience Score of study area a in % (0% means the study area has no flood resilience at all whereas 100% indicates great flood resilience)

$X_{f,a}$: number of buildings/households/infrastructures directly (and indirectly) affected by flood f in study area a

X_a: total number of buildings/households/infrastructures within study area a

In Sections 5.1 and 5.2, the Flood Resilience Score for the overall study area as well as for each neighbourhood within the study area is determined to then be compared to each other and the score of the overall study area.

3.1.5 Phase 3 – Development of spatial design-decision tool for city planners

The third part of the research is dedicated to developing a 3D-city-model-based spatial design-decision tool that city planners and municipalities can use to evaluate their (new) environmental plans based on the Flood Resilience Score introduced in phase 2. During the development of future environmental plans, it becomes increasingly important for city planners and municipalities to not only know which areas within the city are in danger of being flooded before the actual event occurs but also how the future environmental plan influences the movement of water throughout the new urban area as well as in the adjacent areas.

To test a new spatial design idea and to evaluate the potential of a model-based spatial design-decision tool, first, a shapefile layer of the new urban plan is created in QGIS on top of the Open Street Map so that the shapefile has the correct georeferencing. Within the shapefile, polygons are drawn to represent the ground surface of the new buildings and each polygon is given a temporary BAG ID. Then, FME is used to convert the 2D shapefile into a 3D CityGML file. For this example, only LoD1 is needed as the tool is meant to be used in the early stages of spatial planning decisions. Still within FME, additional attributes - that were also added to the former semantic 3D model – are added to the new 3D model. Before adding the new CityGML file to the 3DCityDB, first, the buildings that would have to be demolished to make room for the new environmental plan, have to be removed from the semantic 3D city model. To quickly and precisely remove the correct buildings, the 3DCityDB-Loader and its 'object delete' function is used to remove the buildings within the 3DCityDB. Afterward, the new CityGML file is imported into the 3DCityDB and the data layers in QGIS are refreshed to include the new environmental plans.

After the built environment is adjusted to the new environmental plan, the two rainfall inundation data layers that were also used for phase 1.2 are added to the model and new flood queries are run. The fact that the same rainfall data layers are used even though the built environment within the new environmental plan has changed and so would the results of the hydrodynamic simulation model, is one of the greatest limitations within this research and is elaborated upon further in Section 3.4. The results of the flooding queries are then used to determine the Flood Resilience Scores of the new spatial plan regarding its buildings, households, and infrastructure points. Finally, the results of the Flood Resilience Score are compared to the score of the overall study area as well as to the scores of the individual neighbourhoods to draw a conclusion and give urban planners and municipalities insight into the flood resilience of the new environmental plans.

3.2 Study area

Choosing a study area for this thesis was an iterative process. As 3D BAG covers all of the Netherlands and the BAG register has information on all buildings in the country, in theory, every city could be chosen. This fact, while making the choice for a study area more difficult, also contributes to the versatility and utility of the model. Some additional data, however, is needed such as data on the city's infrastructure network including critical infrastructure points, the number of households living in a building (which is not mentioned in the BAG database due to privacy reasons), and heavy rainfall simulations within the area. On top of that, a municipality's interest in 3D city modelling and innovating decision-making processes can be helpful in gaining access to data from the municipality. In the end, the city of Rotterdam was chosen as a study area as it fulfilled all the requirements and houses the second largest population in the Netherlands, namely nearly 600.000 inhabitants. Therefore, the impact that city planners and their environmental plans have is much greater than in smaller cities.

The municipality of Rotterdam has developed its own 3D city model, called 'Rotterdam 3D' which is available to the public and allows users to view the 3D city and download sections of the model in, among others, CityGML. Which of the two 3D base models - 3D BAG or Rotterdam 3D – should be chosen to build upon, is shortly discussed below and at length in Appendix B.

The third part of this research explores the potential of using the developed 3D flood model as a spatial planning support tool for city planners to evaluate their design plans regarding flood resilience. For this purpose, an existing and ongoing project was chosen; the construction of a new neighbourhood in the north of Rotterdam. 'Nieuw Kralingen' – which is the name of the project but not yet the official name of the neighbourhood – is located in the neighbourhood 'Kralingse Bos'. Figure 34 shows the location of the project within the context of Rotterdam. The already existing plans will be used to evaluate how the plans can be added to the 3D flood model and to evaluate the Flood Resilience Score of the new neighbourhood and its potential effect on the surrounding area.

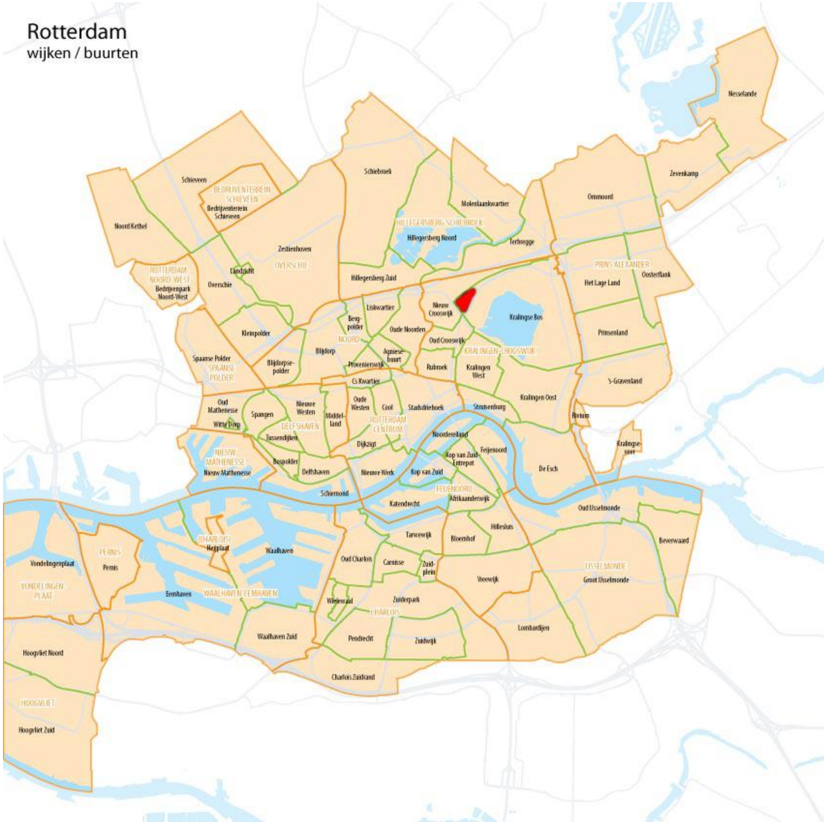


Figure 34. Location of project Nieuw Kralingen (red) in relation to Rotterdam.

With the population rising in all major cities and due to an increasing housing shortage and (apparently) a demand for expensive housing closer to the city centre, the municipality of Rotterdam opted for a large-scale urban development on the fringes of the urban forest of Kralingen which will add up to 800 new residences to Rotterdam. The urban development started in 2018 and will be finalized by 2031 and includes the diversion of the Bosdreef, a highway that currently runs through the development area. OCNK (Ontwikkelcombinatie Nieuw Kralingen) - a consortium consisting of the construction company Heijmans and the real estate developer Era Contour – will be constructing 80 social housing residences for the elderly (rental), 80 medium-income rentals, and 50 medium-income owner-occupied homes. The remaining - and largest share of the residences - will cater to high-income families who want to own their homes (Gemeente Rotterdam, n.d.-b). Figure 35 depicts the layout of the Nieuw Kralingen project and Figures 36 to 38 give an impression of what the neighbourhood will look like at the end of the urban development project.

Figure 35. Layout of 'Nieuw Kralingen' including legenda (Nieuw Kralingen, n.d.).

Figures 36 to 38. Renderings of Nieuw Kralingen (Top010, 2022).

A semantic 3D model of Rotterdam that includes the results of a heavy rainfall and evaluates the flood resilience of the city requires a lot of computational power and decreases image processing which results in a model that does not run smoothly. Therefore, instead of analysing all of Rotterdam, the area surrounding Nieuw Kralingen and its corresponding 3D model is used as the study area for this research. Figure 39 shows a rough estimation of the study area surrounding Nieuw Kralingen. The exact study area and the reasons for choosing it are discussed in more detail in Appendix B, as the chosen study area also depends on the base 3D city model that is used. Other neighbourhoods that fall within the study area besides Kralingse Bos are Hillegersberg Noord, Hillegersberg Zuid, Kralingen Oost, Kralingen West, Nieuw Crooswijk, Oud Crooswijk, Oude Noorden, Struisenburg, and Terbregge.

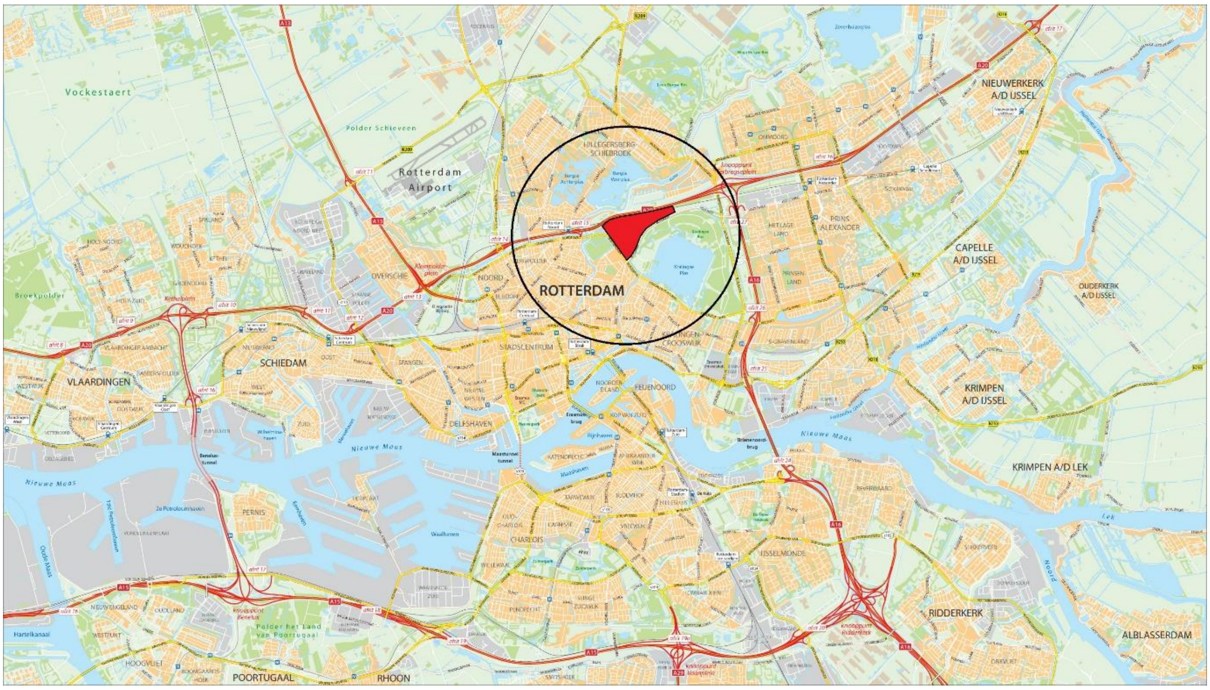


Figure 39. A rough estimation of the study area. Map alternated by the author based on Blokplan (n.d.).

Taking an even larger study area into account - such as the whole city of Rotterdam - is more essential when data on the interconnectedness between infrastructures is available and modelled as the effects of a disrupted infrastructure network are often reaching far beyond the flooded area and across several networks. An extreme flood for example often leads to a power outage that disables the telecom network, which then means that people are unable to call for aid and first responders do not know where they are needed to alleviate some of the effects of the flood.

However, as the data on the interconnectedness between Rotterdam's infrastructure networks is not available, but instead critical infrastructure points are taken into consideration, a smaller study area is more efficient.

3.3 Data management

The following Chapter explains what kind of data was collected for this research, where it was collected from, and how it was processed, validated, stored, visualized, and quantified (Section 3.3.1), and describes the software that was used throughout the research (Section 3.3.2).

The overall system architecture depicted in Figure 40 shows the expected process of the research at the start of this thesis. First data on buildings, building attributes, critical infrastructure points, bridges and trees, and flooding is collected from different sources. Most of the data, except for the building attributes are acquired in file format, making the 3D city model to be developed rely on files rather than databases which would make the model more dynamic and more easily adaptable to future changes in the built environment. The data in the sourced files is then validated, and enriched in FME using an ETL (Extract, Transform, Load) process and a WFS connection to Kadaster's BAG database. From there, the newly created CityGML files are loaded into the 3D Model Database '3DCityDB'. The CityGML files are also added to the 3D database as well as the results from a hydrodynamic flood simulation which are first generated on the servers of 3Di and then loaded into the database through a plug-in that sends a request back to the flood model when the built environment or the requested flood scenario is changed. The semantic 3D city model and the flood are then visualized in Cesium where a City Planner can inspect the visual extent of a flood. At the same time, a GUI (Graphic User Interface) is added to the visualization that uses the 3D data within the database to query the Flood Resilience Score of the study area. Through the GUI, the city planner is then able to upload their new environmental plan into the 3D model database which will start the process of requesting new results from the hydrodynamic model, visualizing the 3D city flood model in Cesium and calculating the Flood Resilience Score anew.

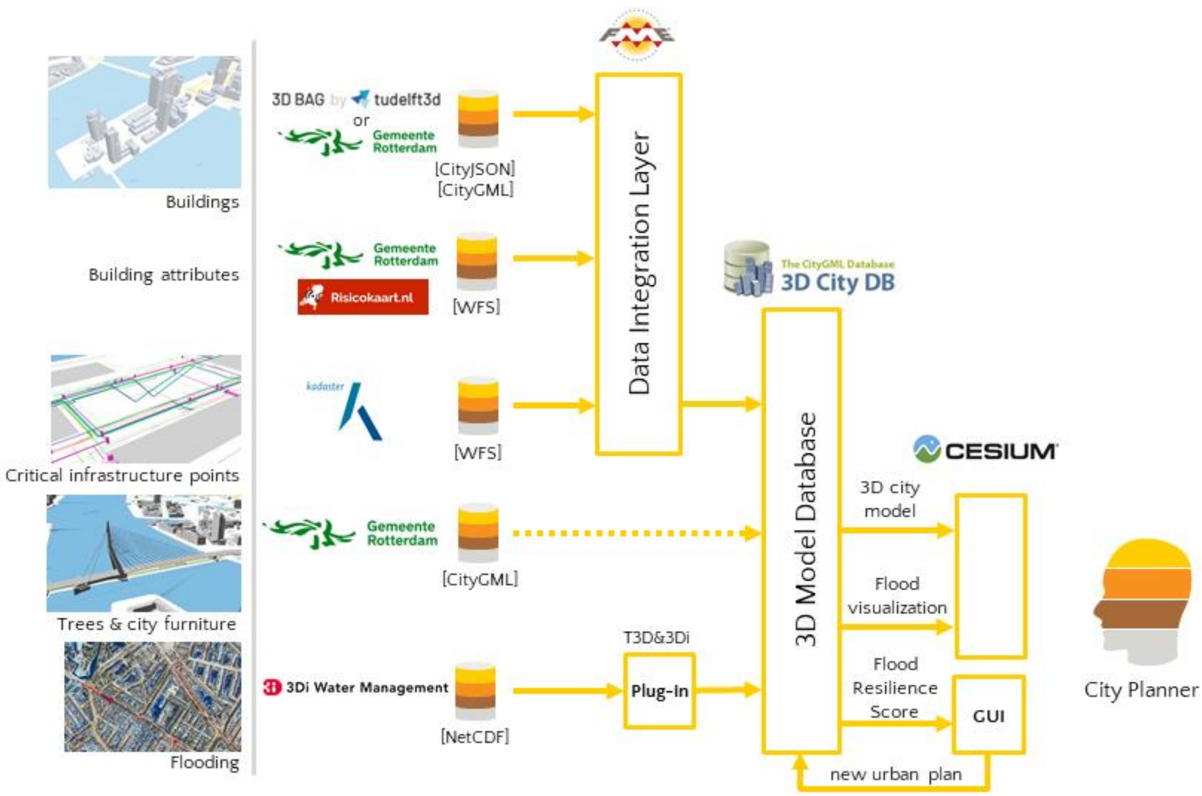


Figure 40. Expected system architecture

3.3.1 Data collection

The validity and utility of this research are highly dependent on the data collected. Throughout the process, it became clear that the required data had to be freely available, represent the reality, and overall be of good quality and from a trusted source.

The literature review shows that 3D cities can be modelled in different environments. Choosing the right environment depends on the requirements of the research. Two important objectives for this research are that the model has to be compatible with file formats used in the built environment sector and that – even though research is slowly moving away from storing all information in one file due to among other data inconsistency, data redundancy and difficulty to data access - a file type has to be chosen that can store information on objects as this thesis has no access to the initial databases. The data format CityGML is able to deliver on both objectives and is also regularly used by cities to represent their 3D city models, which is also the case for the city of Rotterdam. There are two 3D city models of Rotterdam that exist and are publicly available; 3DBAG and Rotterdam 3D. Appendix B analyses which of the models should be used as the base model for this research. The conclusion of the analysis indicates that Rotterdam 3D should be used as the base model. Next to the building layer, the municipality of Rotterdam also supplies the user with CityGML files of solitary vegetation objects (trees) and city furniture (including among others street lights, bicycle racks, and parking meters).

To be able to evaluate the effects of a flood, the buildings in the base model are enriched with additional information including information on;

1. their function(s),
2. their address(es),
3. the neighbourhoods they are located in, and
4. the number of households in each building (which is derived from the number of residential functions in a building).

All this information is collected from the Dutch BAG ('Basisregistratie Adressen en Gebouwen' = addresses and building registration) using a Web Feature Service (WFS) that connects the BAG database to FME (a software that is able to manipulate CityGML files and is further elaborated upon in Section 3.3.2) and extracts all the required data from BAG into the CityGML file. A better process would be to avoid storing data in files and immediately connect an API service to the 3D database. This, however, is not possible as the chosen 3D database requires the data to be supplied in a CityGML file and the data of Rotterdam has to be manipulated in a certain way to be able to import it into 3DCityDB.

At the same time, information on vital, vulnerable, and dangerous infrastructure points has to be added to the base model which is done by finding all the buildings that were labelled as critical infrastructure points in Section 2.1.5 using Google Maps, Atlas Leefomgeving (n.d.) or eduGIS (n.d.) and adding each building, its BAG ID, if it is a critical infrastructure point and what type of point, and flood resilience function and description to an excel document. The excel document is then connected to FME so that the additional attributes of buildings that are also critical infrastructure points, can be added. In this case, using a WFS or API to connect to a database containing critical infrastructure points would make the process more dynamic, however, such an open database does not exists which is probably a benefit for society in light of security and safety reasons.

The two flood inundation maps – the outputs from the flood simulation model that are combined with the semantic 3D city model - are downloaded from the Klimaateffectatatlas (n.d.) which is managed by the independent research institute Deltares. The maps are only available in TIF format which means that the raster layer has to be converted to a vector layer so that it can be combined with the semantic 3D city model.

The last dataset that is used for this research is the shapefile of Nieuw Kralingen. This shapefile is not openly available, therefore, the available urban plan in the form of a .jpeg is used to create a shapefile in QGIS. While these plans are real, it is unclear how many households – of the total of 800 residences will live in each building. To be able to calculate the Flood Resilience Score in regard to the number of households affected, the 800 residences are divided over the 584 buildings. This is the only dataset used in this research that is not based on real data.

3.3.2 Software

To solve the research problem and formulate a method to develop a semantic 3D city model in combination with a flood simulation model which can evaluate the flood resilience of a study area as well as evaluate the flood resilience of future environmental plans, different types of software are used. These software are overall used to store 3D city data, edit data, visualize data, or calculate the Flood Resilience Score. In the following, the software that was used is described in more detail. The latter task – calculating the Flood Resilience Score - is executed using Excel.

3DCityDB

As mentioned before, the free 3D geo-database '3DCityDB' - which can encode CityGML - is utilized to store the semantic 3D city model. Developed as an Open Source and platform-independent software suite, the relational database allows its user to import, manage, analyse, visualize, and export virtual 3D city models according to CityGML 2.0 standards (Yao et al, 2018). By using a database, duplicate data can be avoided, maintenance of the data is more efficient, and updating data is possible.

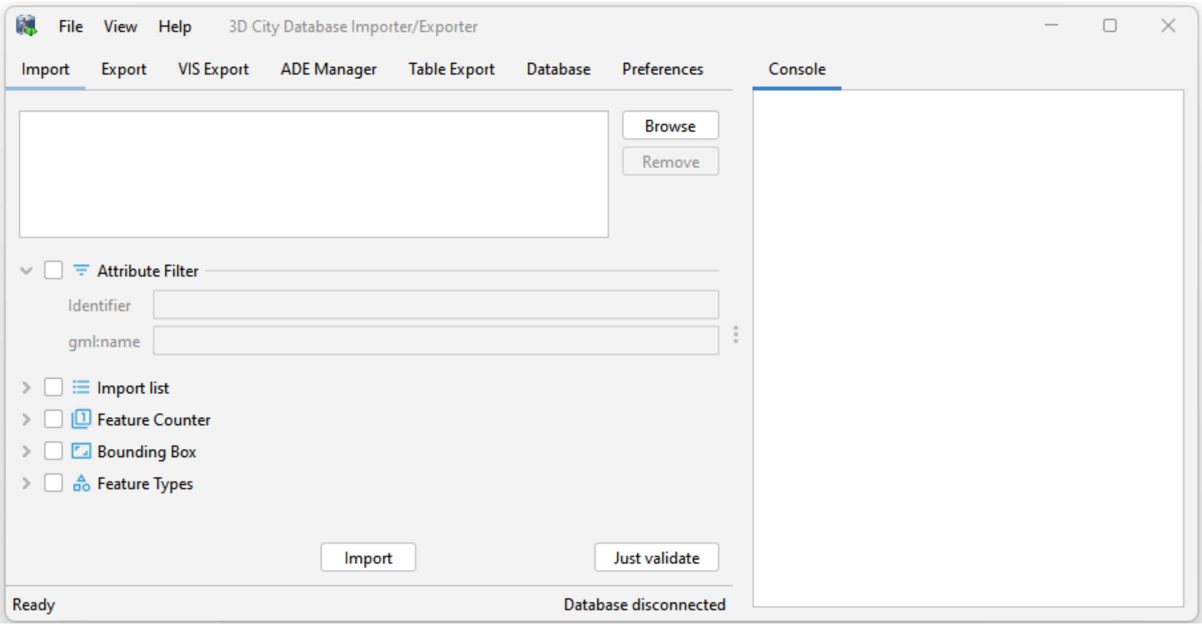


Figure 41. Interface of the Importer/Exporter tool of 3DCityDB.

Through its Importer/Exporter tool (see Figure 41) CityGML files can be imported into a schema and stored across 66 prepared tables in PostgreSQL. Before importing new CityGML files, however, the files should first be validated which the tool also does. Therefore, the tool is also used to geometrically validate the enriched files. The same tool can then be used to export directly to KML, COLLADA, and glTF which can subsequently be used in applications such as Google Earth Pro, ArcGIS, or the web-GL-based Cesium Virtual Globe. To manage and analyse the data in the object-relational database management system PostgreSQL, the loadable procedural programming language PL/pgSQL ('Procedural Language/Postgres Structured Query Language') is used to run queries on the data. The language allows procedural control as well as the ability to use loops and other control structures such as performing complex computations and grouping a series of queries. By using PL/pgSQL, multiple rounds of query parsing can be avoided.

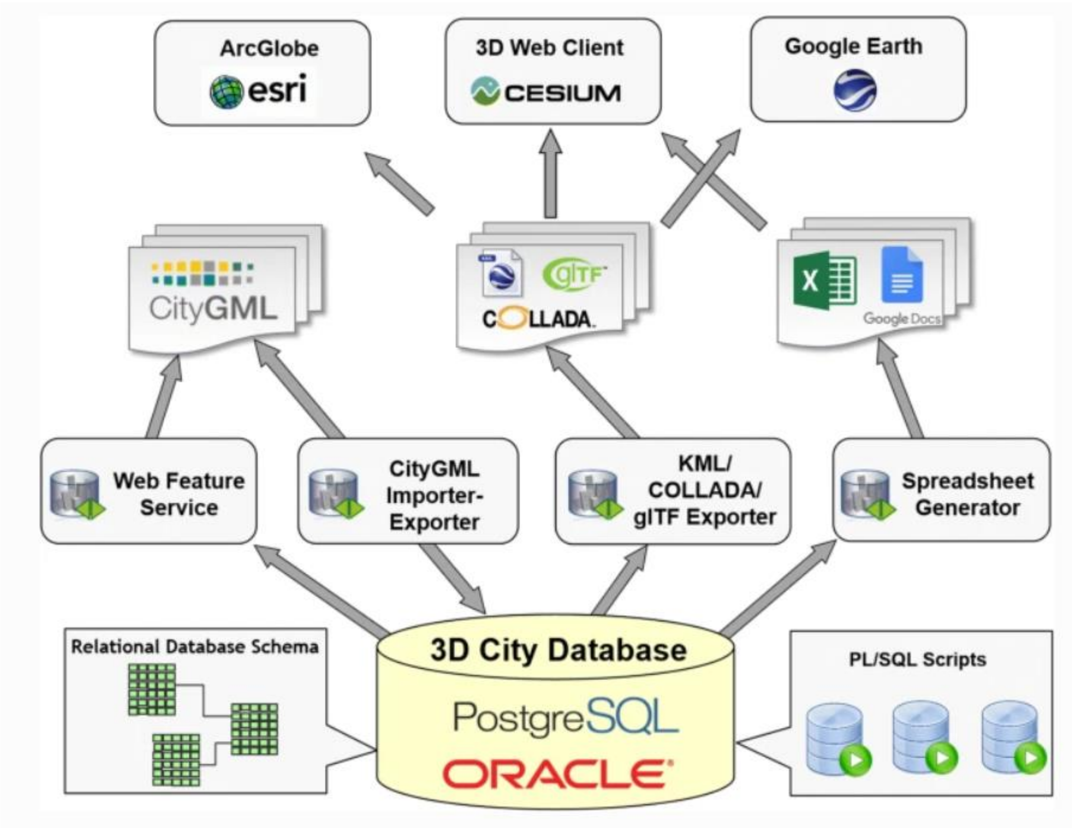


Figure 42. Key components of the 3DCityDB Software Suite (Yao et al, 2018).

Because 3DCityDB is able to process large 3D models which makes the software suitable for storing 3D data of megacities, cities such as Berlin, Potsdam, Frankfurt, Vienna, Salzburg, Singapore, Helsinki, Zurich, Rotterdam, and the Hague all have adopted 3DCityDB to manage their (semantic) 3D city models (Jie et al, 2019).

FME

To edit, manipulate, and enrich the CityGML files with additional data, 'FME Workspace' is used, a data integrated platform that allows to connect and transform data between a multitude of systems while supporting spatial data. FME Workbench uses visual scripting to change the schema and structure of the data (see Figure 43).

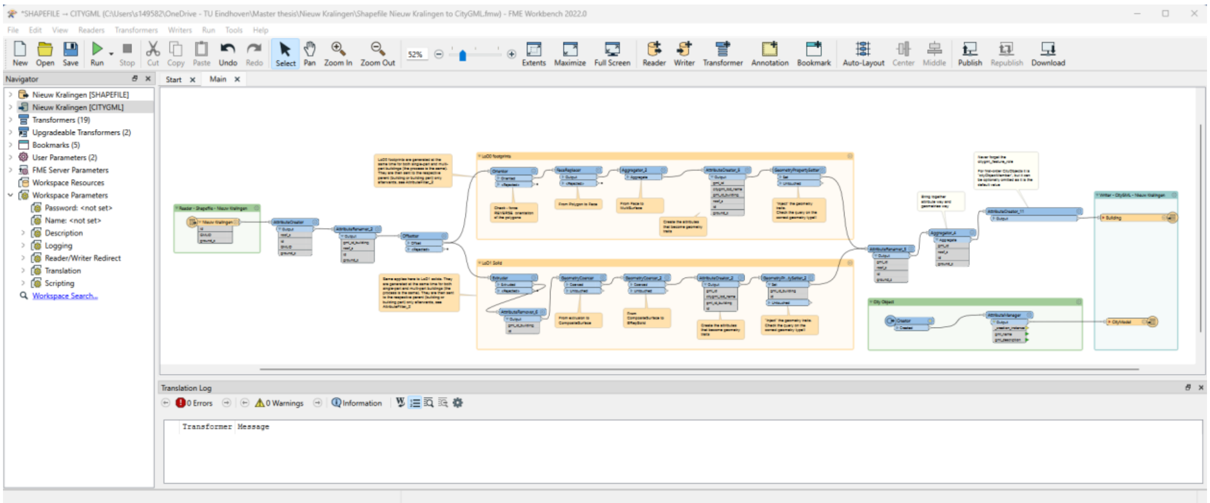


Figure 43. Interface of the FME Workbench including an example of a visual script.

The manipulation of the data is conducted using three primary components; reader, writers, and transformers. ‘Readers’ tell FME which data format is used, where the data set can be found, and which parameters to use when reading the data while ‘writers’ tell FME what data the user wants to end up with and how the new datasets should be written based on a set of parameters. The third primary component of a visual script are transformers which reorganize data structures and change data content between reader and writer.

Another feature built into FME is the ‘FME Data Inspector’. This software allows the user to preview the data before its translation and to verify the data after the translation. Alongside a visual representation of the 3D data model, the embedded information can also be inspected either through the ‘Feature Information’ or using the ‘Table View’.

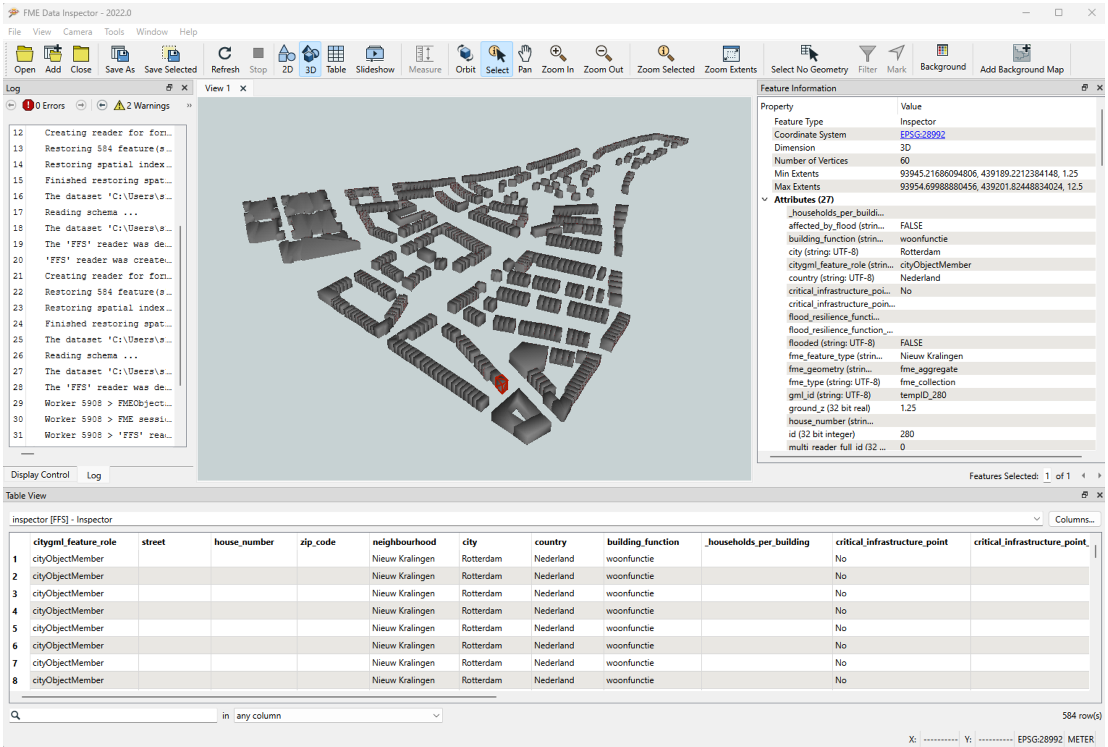


Figure 44. Interface of the FME Data Inspector using a 3D model example.

QGIS plugin - 3DCityDB-Loader

Throughout the research, the 3DCityDB-Loader[1], developed by Pantelios (2022) for his master thesis and further developed by geospatial researchers of the TU Delft and first released in June 2022, is utilized. The tool is able to add flood layers to the semantic 3D city model, to edit attributes, and to delete features. These tasks, while complicated and time-consuming using the 3DCityDB and FME, are made much simpler using the 3DCityDB-Loader. The loader is a free QGIS plug-in that connects the 3DCityDB and its 3D city data to QGIS and translates all changes made to the data in QGIS back to the 3DCityDB. At the same time, the user-friendly QGIS makes it easier to load the 2D flood layers into QGIS and run spatial analyses on the data to see where objects and water intersect. This way, the flooded objects and critical infrastructure points can be queried. At the same time, buffers around vital and dangerous infrastructure points can be created and their reach quantified by adding the objects within their reach to the affected number of objects. While the plug-in allows the user (depending on the user's privileges) to edit the attribute of a feature one at a time and also delete objects (in bulk), the editing of geometries using the loader is not possible. To guarantee that changes made to the date are done so correctly, the software makes use of built-in checks.

QGIS plugin - Qgis2threejs

During parts 2 and 3 of the research, the Qgis2threejs plugin is utilized to visualize the semantic 3D city flood model in QGIS. Through the plugin's interface, the layers that should be visualized can be either turned on or off.

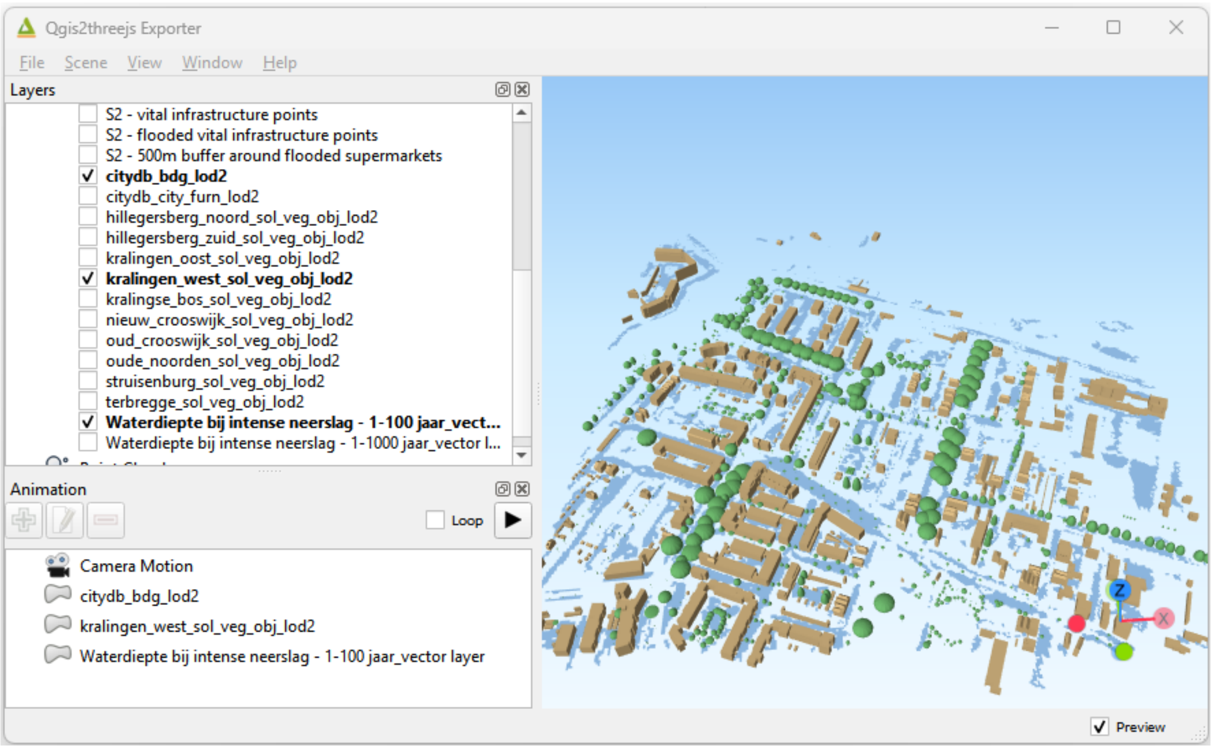


Figure 45. Interface of Qgisthreejs Exporter using an excerpt of the semantic 3D city flood model.

[1] https://github.com/tudelft3d/3DCityDB-QGIS-Loader

FZK Viewer

This research makes use of two openly available software packages to visualize the data; FZK Viewer and Qgis2threejs Exporter. The FZK Viewer (Version 6.3) - developed by the Karlsruhe Institute of Technology (KIT) - is used during the first part of the research to visualize the base 3D city models and inspect the general attributes of each CityGML file (see Figure 46). Overall, the tool is able to visualize semantic BIM and GIS data models such as IFC files, GML files, gbXML files, LandXML files, CIM files, and PointCloud files. A negative aspect of the software is that it has the tendency to 'freeze up' when loading the CityGML file of a neighbourhood into the program, which is probably due to its low processing capacity.

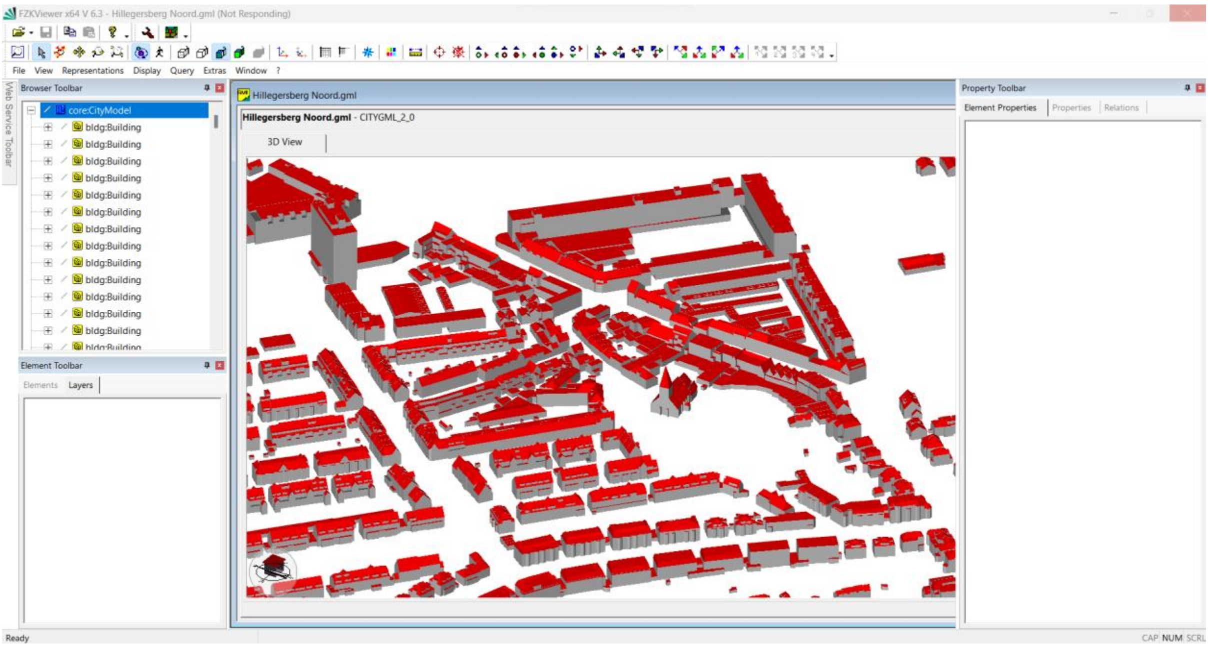


Figure 46. Interface of the FZK Viewer using a 3D model example.

Remaining software

Throughout the process of conducting this research, other software was also explored and used but was found to be either less prominent for the research to be mentioned in detail, not applicable anymore due to a change in direction of the research, or another software tool was used in its place.

During the comparison of the two 3D base models in Appendix B the tool 'Converting CityGML to/from CityJSON' was used to convert the downloaded CityJSON file to CityGML so both models could be properly compared.

'Ninja', a web viewer for CityJSON files developed by the TU Delft was used throughout the research to quickly inspect 3D BAG models to for example find out how many objects are within an area, if generic attributes are included, or to have a look at the code of the CityJSON. Ninja also allows its users to edit the files. Editing the code of the CityJSON files however is not recommended as there is a great chance that by manually editing the file, it will become invalid or corrupted. Instead of using Ninja to edit the code, cjio (also known as CityJSON/io) was used to process and manipulate CityJSON files. In the end, however, the 3D base model of Rotterdam was chosen which meant that CityGML would be used instead of CityJSON and therefore the web viewer and the cjio were no longer needed.

Another important part of the research is visualizing the semantic 3D city model and the flood layer. There are several tools that are capable of doing so. 'Google Earth Pro' and 'Cesium' are both software that were explored, but in the end, it was decided to use the visualization tool 'Qgis2threejs'.

3.4 Limitations

Due to the great scope and state-of-the-art of the topic of open 3D city flood models, the research is faced with many limitations. The most important limitations are briefly discussed below.

3.4.1 Open data and software

This research only uses openly and freely available data and software to test the boundaries of what is possible within the given means to foster accessibility to a wider range of individuals and organizations, benefitting them regardless of their resources of expertise. However, by choosing to only use open data and software, this research also limits itself in exploring the technical limits of dynamic 3D city flood models. Instead, a static 3D city flood model is developed as the open data is only available in file formats and no direct connection to the databases - through for example a WFS or API – can be established except for the BAG database.

3.4.2 Interdependency of infrastructure networks

The literature research showed that infrastructure networks are highly dependent on each other. Modelling this interdependency is therefore important to understand the actual, indirect impact that a flood has on a city. For a thesis that focuses on freely accessible data, however, it is very difficult if not impossible to acquire information on infrastructure networks and it is even more difficult to discover the interdependencies between these networks. Therefore, so-called 'infrastructure points' were chosen for this thesis. These points represent openly available information on the function of each building and the vital, vulnerable, or dangerous role these buildings play during a flood. What these points do not include due to a lack of data, are critical points for infrastructure networks, such as the electricity network or the telecommunication network. If the data on these infrastructure points were to be available, however, it could easily be implemented into the semantic 3D city flood model being developed in this thesis. However, the chances of information on critical infrastructure points becoming public knowledge is small because the released location of some of the points might pose a security risk.

3.4.3 Adjusting the built environment in the flooding model

The last development phase (Section 5.3) focuses on developing a spatial planning support tool to evaluate the flood resilience of potential future environmental plans. To correctly evaluate the effect a flood would have, not only the new built environment has to be added to the 3D city model, but the model that generates the flood results also has to change accordingly to take into account potential changes such as the ground height (an adjusted AHN), surface slope, and surface permeability as well as additional obstacles (buildings) that might influence the behaviour of the water. This, however, is not possible as only openly available data was used and full access to a flood simulation model is not free. In other words, the flooding results used in the last development phase are based on the current situation and not on the potential future situation and therefore the Flood Resilience Scores derived for Nieuw Kralingen do not fully represent the situation that can be expected.

3.5 Conclusion

To summarize, this chapter focuses on the approach of this research. First, the research design which is divided into phases is explained in more detail. Overall, the phases focus on - based on the findings of the literature review - the creation of a semantic 3D city model and connection to a flood simulation model, followed by the development of a Flood Resilience Score which can evaluate the flood resilience of the studied area. Finally, the research will explore the potential of turning the newly developed 3D city flood model into a spatial planning support tool.

The chapter then goes on to detail the process of choosing a city to study and further on to choose a study area within the city. In the end, it was decided to investigate 10 neighbourhoods of the city of Rotterdam, namely Hillegersberg Noord, Hillegersberg Zuid, Kralingen Oost, Kralingen West, Kralingse Bos, Nieuw Crooswijk, Oud Crooswijk, Oude Noorden, Struisenburg, and Terbregge. An 11th 'neighbourhood' that is to be built within the study area called Nieuw Kralingen is chosen as a test case to explore the potential of the model to function as a spatial planning support tool.

Next, the research approach explains what kind of data was collected for this research, where it was collected from, and how it was processed, validated, stored, visualized, and quantified, and the software that was used throughout the research.

Finally, the most important limitations that this study faces are shortly discussed. These limitations include the limits to only using open data and software, the difficulty of modelling the interdependency of infrastructure networks, and the inability of this research to adjust the built environment in the hydrodynamic flood simulation model to represent the environment of the new urban plan.

4. Development of semantic 3D city flood model

This chapter focuses on developing a data-enriched 3D city flood model of Rotterdam. This 'base' model can then be used to evaluate the effect that a flood has on a city (Chapter 5) and serve as a spatial planning support tool for city planners (Section 5.3). To develop the data-enriched flood model, first, the 3D city model needs to be set up including obtaining 3D city data of Rotterdam, checking this data to see if it is valid, storing the data in the 3DCityDB, and visualizing it in Google Earth Pro (Section 4.1). Then, the CityGML files that store the initial 3D city data are enriched with additional information on buildings, important infrastructure points, and other fixed built environment objects such as city furniture and vegetation using the FME Workbench (Section 4.2). Next, two flood scenarios and their resulting inundation maps are connected to the 3D city model in QGIS, using the 3DCityDB-Loader to connect the model stored in the 3DCityDB to QGIS and the resulting 3D city flood model is visualized (Section 4.3). Finally, a conclusion is drawn in Section 4.4.

4.1 3D city model set-up

To develop a data-enriched 3D city flood model, first, a 3D city model needs to be set up. Before the 3D city data can be stored in the 3DCityDB, the data of Rotterdam has to be obtained and then checked for errors by validating the script and visualizing the 3D data. Afterward, all the 3D data files representing buildings of Rotterdam are imported into the SQL-based 3DCityDB. To check if the 3D city model is set up properly, the dataset is exported and then loaded into Google Earth Pro to visualize the model. Figure 47 depicts the process of the 3D city model set-up.

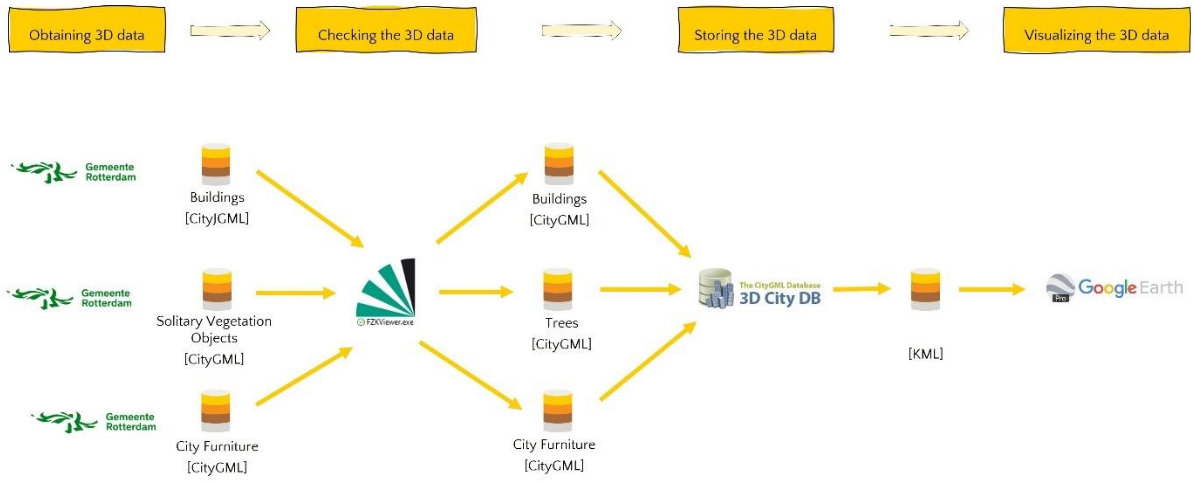


Figure 47. Process of 3D city model set-up.

4.1.1 Obtaining 3D city data of Rotterdam

The 3D data of the buildings in the study area is obtained from the municipality of Rotterdam. The building data is provided in several files, all covering a neighbourhood within the study area. The research area can also be downloaded through the Rotterdam 3D Viewer which allows the user to select a self-drawn area or object in the model, the content of the file such as city furniture, buildings, bridges, or solitary vegetation objects, the preferred file format, and the LoD. CityGML files per neighbourhood for solitary vegetation objects and bridges are also available on request from Rotterdam 3D through an order form on their website. So far, the municipality of Rotterdam has modelled 'special' bridges. such as the Erasmus bridge. However, none of the 'special bridges are located within the study area.

Among others, the content of the building files contains feature attributes such as a unique BAG ID for each object ('gml_id' and 'gebouwnummer'), the year the building was constructed ('citygml_year_of_construction'), the height of the building ('citygml_measured_height'), the number of storeys a building has ('aantalBouwlagen'), and the current phase in the building's life-cycle ('statusOmschr'). Building attributes such as the function of the building, the addresses listed for each building, and the number of households living in each building, are missing.

4.1.2 Checking the 3D data

After gaining access to the available 3D city data, the files need to be checked to see if they contain any geometric or topological errors such as missing surfaces, duplicate vertices, or self-intersecting volumes. To do so, two validations are run; a visual check and a geometric validation.

Visual check

After downloading the CityGML files containing the built environment of Rotterdam, the data is first visually checked using the FZKViewer developed by the Karlsruhe Institute of Technology.

Figure 48 depicts two conducted visual checks, one of the CityGML file containing the buildings in the neighbourhood Terbregge and the other one of the tree coverage in Terbregge.

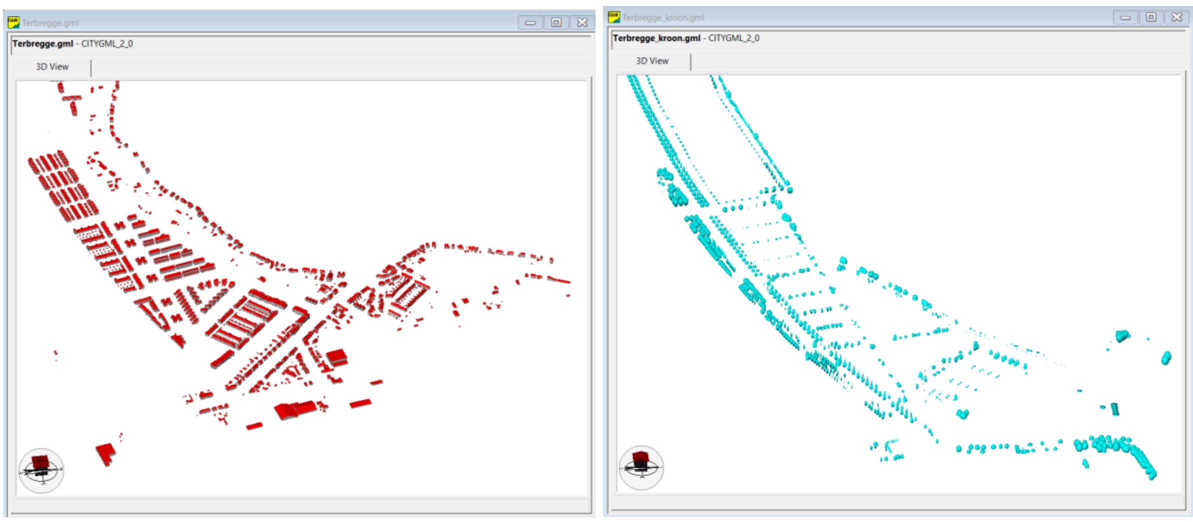


Figure 48. Visual checks in the FZKViewer of the building and tree coverage in Terbregge.

Geometric and Schema validation

There is no easy-to-use and readily available software that checks if a CityGML dataset respects the standardised specifications and definitions as given in the 'OGC CityGML Encoding Standard' to see if the XML Schema and the geometric primitives of CityGML are valid. However, software such as FME or 3DCityDB that manipulate or store 3D data, have validations built-in which can be turned on when importing or writing data. The geometric and schema validation will therefore take place when the CityGML files are manipulated using FME. The errors leading to a potentially invalid file will then be resolved using the FME workbench.

Completeness of checked data

Retrieving and checking the 3D data for Rotterdam is a long process because of the way the data is exported. The municipality of Rotterdam has opted for creating files for each neighbourhood or for an area not greater than 2.000.000m^2, instead of making all of Rotterdam accessible in one file which is reasonable when considering the potential file size. However, by for example converting a CityGML to CityJSON the municipality would be able to reduce the file size significantly and make the whole 3D city model of Rotterdam accessible in one CityGML file (van Liempt, 2020). Because the manual process of checking each file separately takes a long time, out of all files, a spot check is done to see if the chosen files are valid. However, this does not mean that the files that are not visually checked and geometrically validated according to ISO 19107, are not validated at all. Throughout the process of the research, 3D data is constantly checked visually and compared to the real built environment to detect and eradicate any errors. Furthermore, when importing the 3D city data into the 3DCityDB, the importer also validates the schema of the CityGML files.

4.1.3 Storing the 3D city data in 3DCityDB

To be able to store the 3D city data that was obtained and checked in the former steps, the SQL database 3DCityDB first has to be set up. A detailed description on how the 3DCityDB is set up can be found in Appendix D.

If the setup was successful, two schemas – 'citydb' and 'citydb_pkg - are automatically added to the PostgreSQL database. The 'citydb' schema is a default schema that can store the 3D city database while the 'citydb_pkg' contains scripts that create database objects and store procedures used by the Importer/Exporter tool. The advantage of using multiple schemas instead of multiple databases for different projects/data within one project is that tables from different schemas can be joined while queries across databases are much more difficult if not impossible in PostgreSQL. Additional schemas are therefore created to store data separately and to be able to evaluate the neighbourhoods separately.

After the 3DCityDB is set up, 3D city data has to be imported into the SQL database using the Importer/Exporter tool. However, only data with a CityGML or CityJSON file format can be imported. Before importing the data, the file should be validated (an option that is included in the tool) to prevent unexpected behaviour or abnormal termination. Before executing the importer, the user is able to set parameters such as a bounding box for the data that should be imported in case the file is larger than needed. Another parameter that the user can set is the attribute filter which filters the data based on a certain identifier. After importing the 3D city data, the data is checked to see if it was correctly imported by requesting a database report. The database in the console window (see Figure 49) shows a list of all tables of the 3DCityDB including their total number of rows.

```
Console
[13:27:45 INFO] Generating database report...
Database Report on 3D City Model - Report date: 29.06.2022 13:27:45
==================================================================
#ADDRESS                         19342
#ADDRESS_TO_BRIDGE               0
#ADDRESS_TO_BUILDING             19342
#APPEAR_TO_SURFACE_DATA          0
#APPEARANCE                      0
#BREAKLINE_RELIEF                0
#BRIDGE                          0
#BRIDGE_CONSTR_ELEMENT           0
#BRIDGE_FURNITURE                0
#BRIDGE_INSTALLATION             0
#BRIDGE_OPEN_TO_THEM_SRF         0
#BRIDGE_OPENING                  0
#BRIDGE_ROOM                     0
#BRIDGE_THEMATIC_SURFACE         0
#BUILDING                        27480
#BUILDING_FURNITURE              0
#BUILDING_INSTALLATION           2090
#CITY_FURNITURE                  0
#CITYMODEL                       0
#CITYOBJECT                      342675
#CITYOBJECT_GENERICATTRIB        102584
#CITYOBJECT_MEMBER               0
#CITYOBJECTGROUP                 0
#EXTERNAL_REFERENCE              0
#GENERALIZATION                  0
#GENERIC_CITYOBJECT              0
```

Figure 49. Database report of the study area.

4.1.4 Visualizing the 3D city data in Google Earth Pro

After importing all the CityGML files containing buildings of the study area, the 3D city data is exported to KML and visualized in Google Earth Pro.

Exporting 3D city data

Overall, the Importer/Exporter tool allows the user to export the 3D data in KML, COLLADA, and glTF according to a set of preferences regarding general preferences, rendering preferences, information balloon preference (only available in KML), and altitude/terrain preferences. For the export, the highest LoD available is used to visualize the most detailed version of the 3D model. However, choosing the highest LoD possible also means that the file size is greater and generating and loading processes take longer. The 3D model can be displayed as a footprint, as an extrusion (meaning that the objects are extruded from their footprint to their height, making the objects become blocks), in fully detailed geometry (including the colour of an object but not including its texture), or as COLLADA or glTF (which displays the detailed geometry of the 3D model including textures).

For this research, geometry or COLLADA can be chosen as the model does not contain any colours or textures.

Visualization with Google Earth Pro

The exported KML file is then imported into Google Earth Pro to visualize the 3D city data that was imported into 3DCityDB. Following the trend of the research, Google Earth Pro can be downloaded and used free of charge. When the file is larger than 10 MB, tiling the file is recommended as the responsiveness of Google Earth greatly decreases when the file is greater than 10 MB. The file importer into Google Earth Pro is only 2KB, however, even at a much lower file size, the software's responsiveness is still very low. Still, it is able to display the 3D city data of all buildings in the study area (see Figure 50).

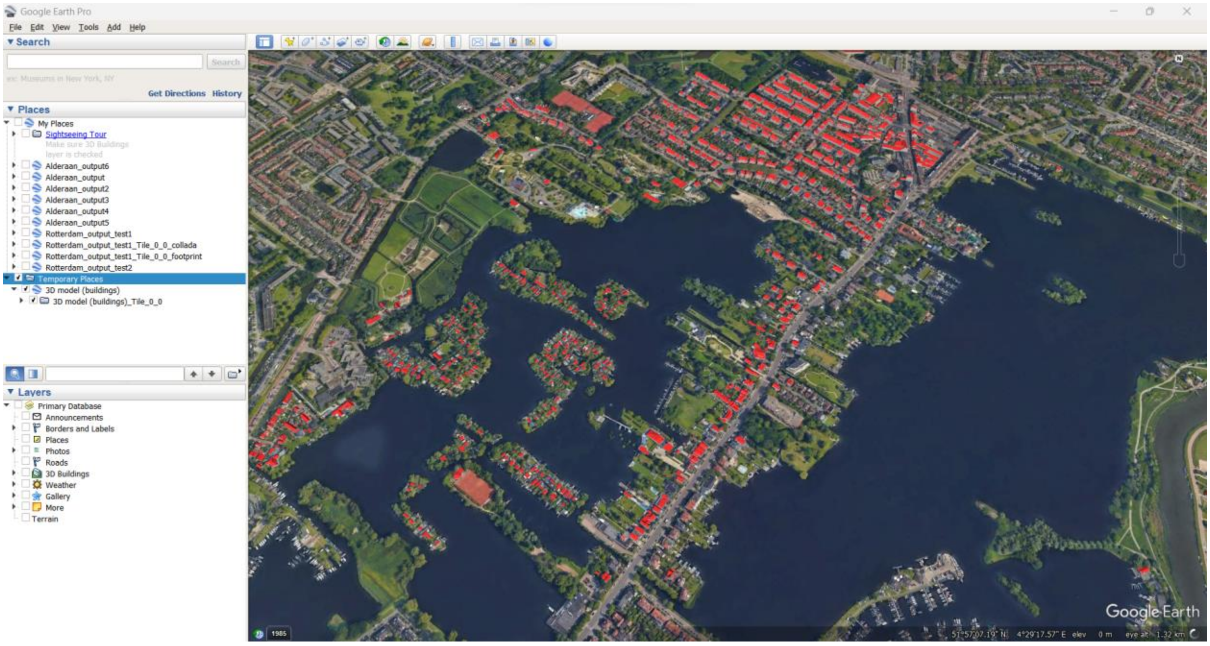


Figure 50. 3D city model in Google Earth Pro.

4.2 Data-enrichment of 3D city model

This chapter of the research focuses on enriching the obtained CityGML files of the 3D city model, with additional data using FME software. The FME workbench is used to develop a visual script that manipulates and expands the schema of the data in such a way that the 3D model is enriched with the data required to evaluate the effect of a flood. Figure 51 depicts the process of enriching the 3D city model with data. The data that is added to the CityGML files containing the buildings includes information on:

- the function of each building,
- the number of households per building,
- the addresses of each building,
- the neighbourhood in which each building is located, and
- the *vital, vulnerable and dangerous infrastructure points* within the study area.

Furthermore, the CityGML files containing solitary vegetation objects and city furniture are debugged and enriched to be added to the 3DCityDB alongside the enriched building files. The full FME workbench can be viewed in Appendix E.

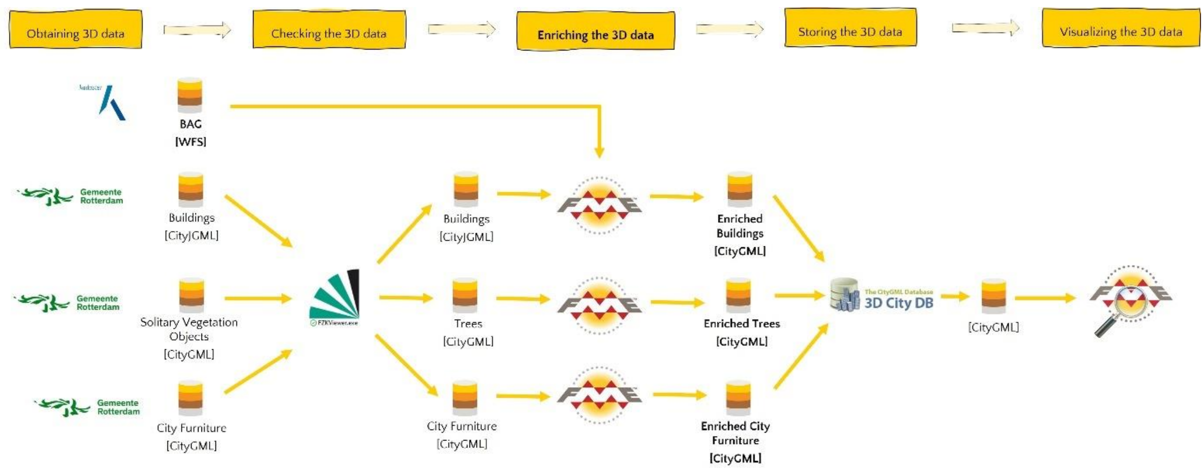


Figure 51. Process of enriching 3D city model with data.

4.2.1 Adding building information to CityGML files

The CityGML files containing information on the buildings that are used for this research are provided by the municipality of Rotterdam in the form of single CityGML files per neighbourhood. The built-in download function of the 3D viewer of Rotterdam also allows its users to download buildings in CityGML form by drawing a box on the map of Rotterdam which can then be downloaded. There is however a limit to the area that can be downloaded - which is further discussed in section 4.2.3 – which makes it a lot easier to use the CityGML files provided by the municipality.

Adding a reader for the CityGML file of a neighbourhood (in the examples below, the CityGML building file for the neighbourhood Terbregge is used) tells the FME workbench which data format is used, where the dataset can be found (either on a computer's hard drive or in the form of a URL), and which parameters have to be considered when reading the dataset. Most of the standard parameter settings remain the same, however, the validation parameter that guarantees that the CityGML dataset file is validated beforehand is switched on. Furthermore, the Coordination System is set to 'EPSG:28992' (referring to the coordination system for the Netherlands), and the GML SRS Axis Order is set to '1,2,3'.

To be able to add additional building information from the BAG database to the CityGML file, a connection has to be made between the BAG database and the FME server. This is done using a Web Feature Service (WFS) which is imported into the FME workbench as a reader using the OGS WFS format and the BAG URL as database path[2]. The feature type is set to only return 'verblijfsobject' ('residences' which here refers to any building where people can reside, not only homes). To return the information of the required buildings, a bounding box/search envelope is defined that covers the whole neighbourhood. If no bounding box is defined, the BAG database will return information on buildings in Appingedam. A list of all the bounding boxes per neighbourhood and the whole study area can be found in Appendix C. The exact parameters of the bounding boxes were calculated by importing the CityGML files from the municipality into the 3DCityDB and letting the database calculate the bounding box. Finally, the maximum number of features (the number of buildings uploaded) has to be set which should cover all buildings in the bounding box and therefore exceed the number of buildings in the CityGML file as the bounding box of the neighbourhood covers a larger area than the neighbourhood itself. Unfortunately, the WFS only allows its

[2] https://service.pdok.nl/lv/bag/wfs/v2_0?request=getCapabilities&service=WFS

users to return a maximum of 1000 residences but the number of buildings in a neighbourhood far exceeds this number. As a result of choosing to develop a file-based model, paging has to be used which is a function of memory management where a computer stores and retrieves data from a device's second storage to the primary storage. For this, the start index is set to 0, the count to 1.000, and the maximum features to a number greater than the number of buildings within the bounding box.

While paging allows the WFS to return a much greater number of features, it is however capped at a maximum number of 50.000 features. This cap is the reason why the complete study area is not immediately enriched with data in one FME script but the scripts are run separately for each neighbourhood. This entails that the source of the CityGML reader needs to be changed, as well as the bounding boxes of the WFS and the destination file of the writer.

To connect the BAG data with the buildings in the CityGML file, a primary key is needed. In the Netherlands, all buildings have a unique building ID also called BAG ID. Looking at the BAG data and the building file shows that both datasets use the BAG ID, however, BAG labels the ID as 'pandidentificatie' while the municipality of Rotterdam names the ID 'gebouwnummer', the values however, remain the same.

Running the CityGML reader shows that 2.125 buildings are stored in the dataset. However, when importing the same CityGML file into the 3DCityDB, the database report (see Figure 52) indicates that there should be 2.631 buildings within the file. When visualizing the feature type 'Building' in the FME inspector it becomes even more clear that about a fifth of the buildings seem to be 'missing'. This has to do with the way the building objects were written into the CityGML file. The municipality has opted to model certain buildings as multi-part buildings instead of single-part buildings which in theory is correct as it depends on how the programmer wants the data to be interpreted. As a result, not all the buildings are visualized when only displaying the feature class 'Building' and leaving out the feature class 'BuildingPart'. Running the 'BuildingPart' feature class shows that the 506 'missing' buildings are indeed classified as part of multi-part buildings. For this research, however, all buildings need to be classified as single-part buildings to be able to enrich the buildings with additional data and therefore the buildings classified as 'BuildingPart' are moved to the feature class 'Building'.

```
[14:56:22 INFO] Generating database report...
Database Report on 3D City Model - Report date: 27.07.2022 14:56:22
===================================================================
#ADDRESS                        2122
#ADDRESS_TO_BRIDGE              0
#ADDRESS_TO_BUILDING            2122
#APPEAR_TO_SURFACE_DATA         0
#APPEARANCE                     0
#BREAKLINE_RELIEF               0
#BRIDGE                         0
#BRIDGE_CONSTR_ELEMENT          0
#BRIDGE_FURNITURE               0
#BRIDGE_INSTALLATION            0
#BRIDGE_OPEN_TO_THEM_SRF        0
#BRIDGE_OPENING                 0
#BRIDGE_ROOM                    0
#BRIDGE_THEMATIC_SURFACE        0
#BUILDING                       2631
#BUILDING_FURNITURE             0
#BUILDING_INSTALLATION          150
#CITY_FURNITURE                 0
#CITYMODEL                      0
#CITYOBJECT                     28383
#CITYOBJECT_GENERICATTRIB       10253
```

Figure 52. Database report of Terbregge.

Figure 53 shows the FME workbench that is used to aggregate the building parts into the building feature class. To do so, an ETL procedure is used. First, the geometries of the building parts as well as all the attributes besides the 'gml_parent_id' are removed followed by the grouping of the remaining attribute. Then, the parent ID attribute is renamed to 'gml_id' to then be merged with the feature class 'Building' on the primary key 'gml_id'. Then, the relevant attributes contained in the building parts, are merged with the buildings. In the end, the enriched buildings and the unmerged single-part buildings are combined. Running the script now indeed shows that all buildings are correctly classified.

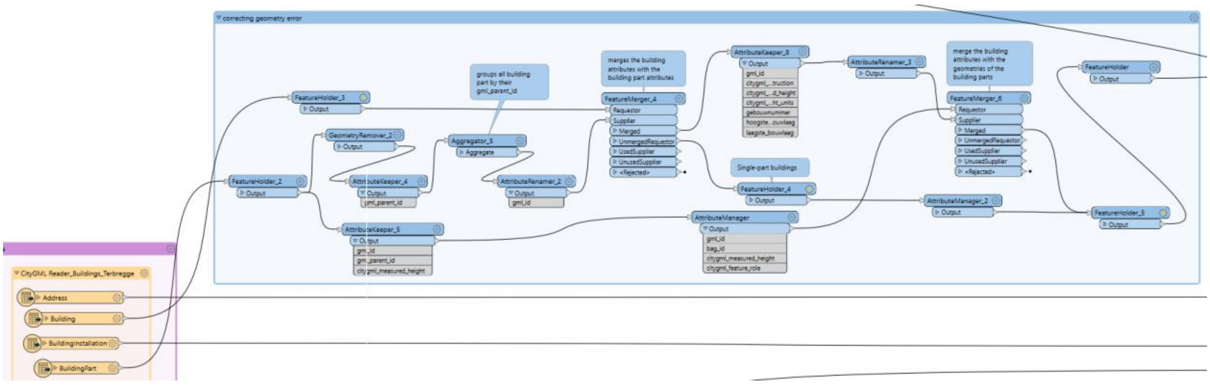


Figure 53. Correcting geometry mistakes of CityGML file in FME workbench.

Information from the BAG is, among others, used to add the number of households per building. Figure 54 shows an extract of the FME workbench of this process. First only the required attributes (function and BAG ID) of the residences are kept followed by filtering all residences by their function ('gebruiksdoel'). Each function that includes a residential function (woonfunctie) is then aggregated to count the number of 'woonfuncties'/households per building. Finally, the newly created attribute '_households_per_building' is merged with the CityGML file on the primary keys 'pandidentificatie' and 'gebouwnummer' and a duplicate filter makes sure that the dataset does not contain any duplicate building IDs. By using the CityGML reader as the requestor for the feature merger, only BAG information on buildings within the study area is passed on. Running the script also shows that there are unmerged requestors. This means that there are buildings within the CityGML file that cannot be matched with any data from BAG. A closer look reveals that the CityGML file also includes objects such as garages or sheds, which the BAG does not list.

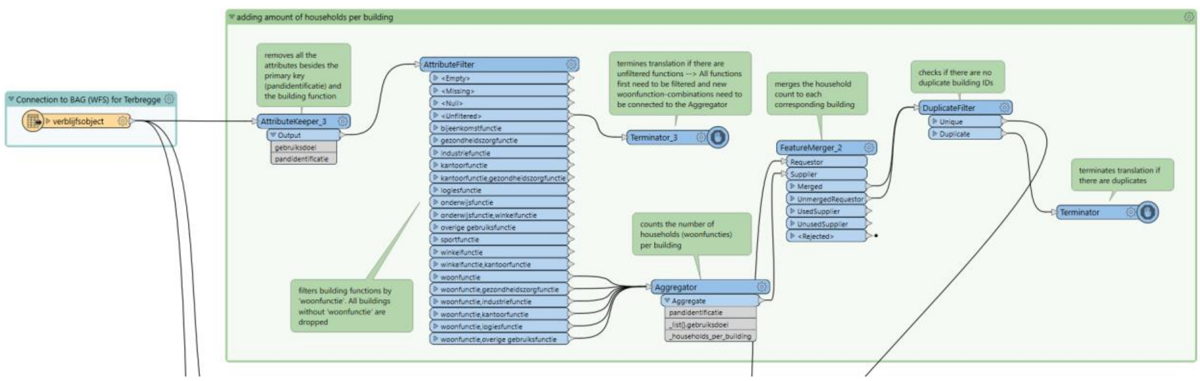


Figure 54. Adding the number of households per building in FME Workbench.

The WFS is also used to add information on the functions of the buildings (see Figure 55). Again, only the required attributes are kept, namely the 'gebruiksdoel' and 'pandidentificatie'. Then the features are grouped by their unique building ID because the BAG bases their features on addresses, while the CityGML file reports a feature as a building ID (a building ID can have several addresses). The aggregator transformer groups the building IDs and at the same time creates a new list attribute '_list_gebruiksdoel{}.gebruiksdoel' which lists all the functions within a building. The list is then alphabetically sorted in ascending order, any duplicates in the list are removed, the list is renamed to 'citygml_function{}', and the two datasets are again merged on their primary key.

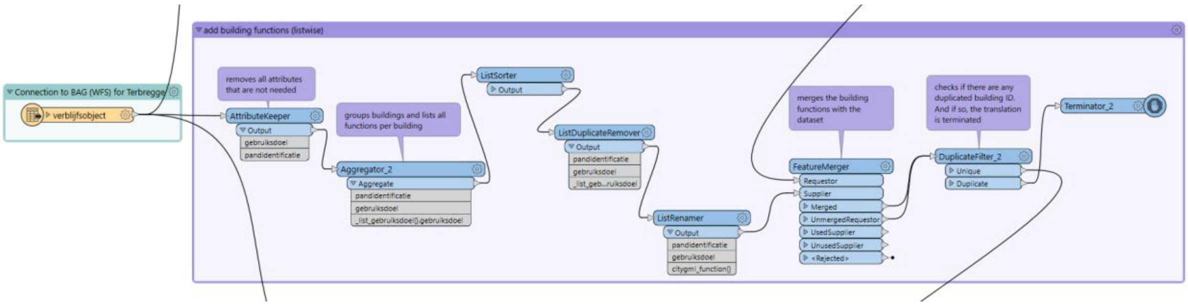


Figure 55. Adding building functions per building in FME Workbench.

For planners to easily see which buildings are affected by a flood, at first, the addresses were also added to the buildings as generic attributes instead of as a feature class of its own. To do so, a new attribute labelled 'address' was created. The value of this attribute was made up of a string of other attributes available in the BAG, namely the street name ('openbare_ruimte'), house number ('huisnummer'), house letter ('huisletter'), affix ('toevoeging'), postal code ('postcode'), and city ('woonplaats'). An aggregator transformer then grouped the building IDs and created an attribute that listed all addresses within the building (sidenote: the address attribute is not a list). Afterward, the features were merged. Figure 56 depicts the extract of the FME workbench that adds the addresses to the buildings. Importing the manipulated CityGML building files into 3DCityDB at a later point in time, however, showed that the Importer/Exporter tool only allows the import of attributes that have a value with a certain amount of characters which the new attribute 'address' by far exceeds. Therefore it was decided to remove the new attribute and rely on the addresses coded as feature classes.

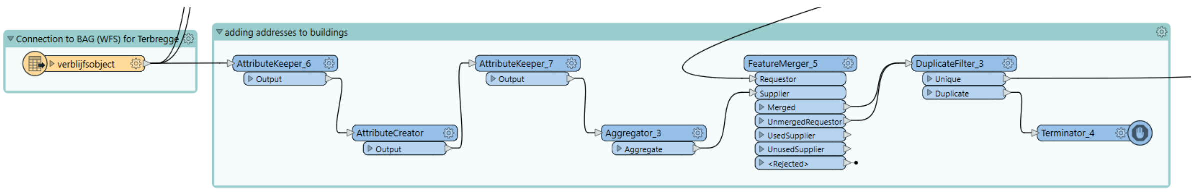


Figure 56. Adding a list of addresses to each building in FME Workbench.

To later on easily distinguish which neighbourhood file the data belongs to, the attribute 'neighbourhood' is added to the buildings in the CityGML file (see Figure 57). Here, the value of the attribute is Terbregge. When enriching another neighbourhood file with building data, this value is manually adjusted to reflect the correct name of the neighbourhood.

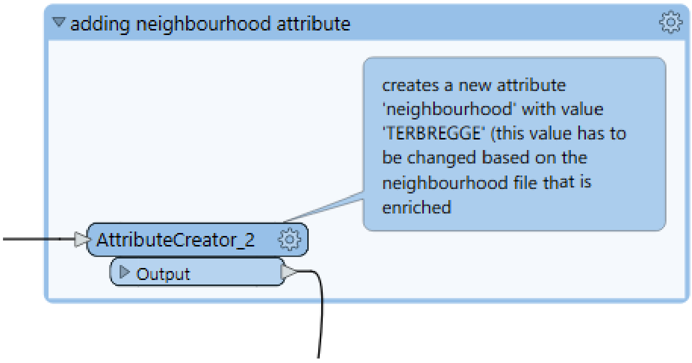


Figure 57. Adding the attribute 'neighbourhood' to each building in the FME Workbench.

In the end, all connections are linked to the imported writer which tells FME what data the user wants to end up with and how the new datasets should be written based on a set of parameters. For this writer, the standard set of parameters is used, however, the validation of the output file is switched on, the GML srsName is set to 'EPSG:28992', the GML SRS Axis Order is set to '1,2,3', and the 'pretty print'-parameter is switched on to make it easier to read the CityGML file when opening it in a text reader. Additionally, all the user attributes that are not standard attributes and that were either added or already in the existing CityGML file, are manually added to the writer as can be seen in Figure 58. The steps to set up a writer are identical (except for the varying user attributes) to setting up a writer for other built environment objects and will therefore not be repeated in a later section.

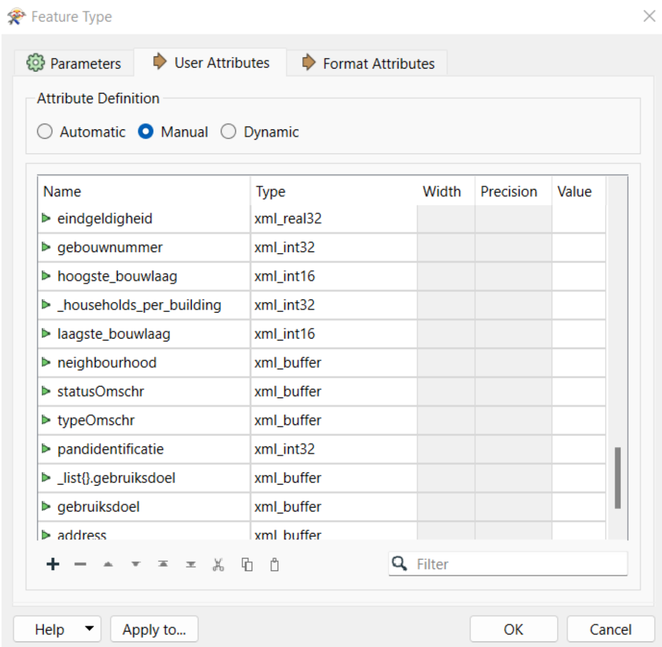


Figure 58. Manually adding user attributes to the writer.

4.2.2 Adding critical infrastructure points

To be able to evaluate the effect that a flood has on the city's infrastructure, the location of critical infrastructure points is added to the semantic 3D city model. This can be done in two ways; the critical infrastructure points can be seen as attributes of objects and therefore added to an object as a generic attribute (the XML schema of any CityGML version does not accept infrastructure points as a feature class, instead, they have to be added as generic attributes) or use CityGML's generics module where each

GenericCityObject (see Appendix A as a refresher) may represent a critical infrastructure point but which does not have to be graphically modelled in the 3D city model.

Classifying critical infrastructure points as a Generic City Object is the more sophisticated option. However, to implement this option, location data (adhering to the Dutch reference system) of the infrastructure points is required in the form of for example another CityGML, CityJSON, or PostGIS file. Instead, the less sophisticated option of adding critical infrastructure points as generic attributes to objects is chosen.

In the Netherlands, the website 'risicokaart' which was created and is supported by Dutch provinces and ministries, maps (infrastructure) risks to the Netherlands from events such as floods or accidents with hazardous materials (GBO provincies, n.d.). Data included are geo-information on vulnerable objects such as hospitals, elderly homes, public buildings, offices, etc. This data can be studied, among others, through the map-viewer 'Atlas Leefomgeving'. To get access to the data, a WFS was installed that creates a connection to the database of the risk map. This WFS, however, is only accessible to people working for the Dutch government or for a municipality which is probably due to the potential security issues when making information on critical infrastructure point public (GBO provincies, 2019). Besides the WFS from the GBO provinces, there is no other public WFS available that connects to a database with information on Dutch critical infrastructure points.

As no database or file type that is supported by FME exists that provides information on the critical infrastructure points within a city, an excel file listing all the infrastructure points and their corresponding BAG IDs has to be generated manually. Before adopting the information provided by the map viewer, the data provided needs to be validated. The BAG IDs in the Atlas Leefomgeving viewer (labelled '*AOBJECTID*') are compared to the official BAG IDs used in Rotterdam 3D (as well as in 3D BAG and in the official BAG database) labelled '*gml_id*' to check if they are equal. A random sample shows that the BAG IDs are not the same. An investigation into the different identification numbers reveals that Rotterdam 3D refers to the 'pand ID' (eng.: building ID) as BAG ID, while the Atlas Leefomgeving calls the 'verblijfsobject ID' (eng.: residence ID) BAG ID. The value of the 'verblijfsobject ID' looks very similar to the 'pand ID' as both values start with 'BAG_' but they are not equal and therefore cannot be used as a primary key. This means that for each building that has to be coded as a critical infrastructure point, the 'pand ID' has to be found. (In the following, the 'pand ID' is again referred to as the BAG ID.).

Alongside the Atlas Leefomgeving viewer, other map viewers are used to collect geo data on critical infrastructure points such as the EduGIS Atlas (EduGIS, n.d.) which depicts the location of the object but not the corresponding BAG ID. With the information available, the following critical infrastructure points are included in the semantic 3D city model;

- Vital
  - Police stations [data source: google maps]
  - Fire stations [data source: google maps]
  - Supermarkets [data source: google maps
  - Hospitals [data source: Atlas Leefomgeving]
- Vulnerable
  - Elderly homes [data source: Atlas Leefomgeving]
  - Monument & world heritage [data source: eduGIS]
- Dangerous
  - Not available

The generated excel file includes the BAG ID ('BAG_ID') of the building that functions as a critical infrastructure point, a Boolean to distinguish between buildings that are either vital, vulnerable, or dangerous during floods ('critical_infrastructure_point'), the type of critical infrastructure point namely vital, vulnerable, or dangerous ('critical_infrastructure_point_type') and the function of the building which contributes to the flood resilience of a city ('flood_resilience_function'). Figure 59 shows an excerpt of the excel file.

	A	B	C	D	E
1	gml_id	critical_infrastructure_point	critical_infrastructure_point_type	flood_resilience_function	flood_resilience_function_description
2	BAG_0599100000626953	TRUE	Vital	hospital	Klinieken (poli-, psychiatr., ...), > 10 pers.
3	BAG_0599100000673939	TRUE	Vital	hospital	Klinieken (poli-, psychiatr., ...), > 10 pers.
4	BAG_0599100000751878	TRUE	Vital	hospital	Klinieken (poli-, psychiatr., ...), > 10 pers.
5	BAG_0599100000763504	TRUE	Vital	hospital	Klinieken (poli-, psychiatr., ...), > 10 pers.
6	BAG_0599100000638403	TRUE	Vital	hospital	Klinieken (poli-, psychiatr., ...), > 10 pers.
7	BAG_0599100000192051	TRUE	Vital	hospital	Klinieken (poli-, psychiatr., ...), > 10 pers.
8	BAG_0599100000608611	TRUE	Vital	hospital	Klinieken (poli-, psychiatr., ...), > 10 pers.
9	BAG_0599100000692649	TRUE	Vital	hospital	Klinieken (poli-, psychiatr., ...), > 10 pers.
10	BAG_0599100000754644	TRUE	Vital	hospital	Klinieken (poli-, psychiatr., ...), > 10 pers.
11	BAG_0599100010030118	TRUE	Vital	hospital	Ziekenhuis, > 10 pers
12	BAG_0599100000700017	TRUE	Vital	hospital	Ziekenhuis, > 10 pers
13	BAG_0599100000684244	TRUE	Vulnerable	Elderly homes	Tehuizen, > 10 pers.
14	BAG_0599100000659656	TRUE	Vulnerable	Elderly homes	Verpleegtehuizen, > 10 pers.
15	BAG_0599100000181399	TRUE	Vulnerable	Elderly homes	Verpleegtehuizen, > 10 pers.
16	BAG_0599100000635366	TRUE	Vulnerable	Elderly homes	Tehuizen, > 10 pers.
17	BAG_0599100000687460	TRUE	Vulnerable	Elderly homes	Tehuizen, > 10 pers.

Figure 59. Extract of data of critical infrastructure points in an excel file.

After creating the excel file - which can be adjusted and expanded at a later time as well to include more critical infrastructure points - the file is added as a reader to the FME script and the critical infrastructures are connected to the CityGML building file by merging the data on the BAG IDs. Figure 60 shows the FME workbench that is used to manipulate the data. This makes the process semi-automatic. However, the potential of making the process fully automated for municipalities does exists with the right access to an up-to-date infrastructure network database. By doing so, the infrastructure dataset could be directly connected to the FME workbench and running the workbench would automatically update the resulting CityGML file.

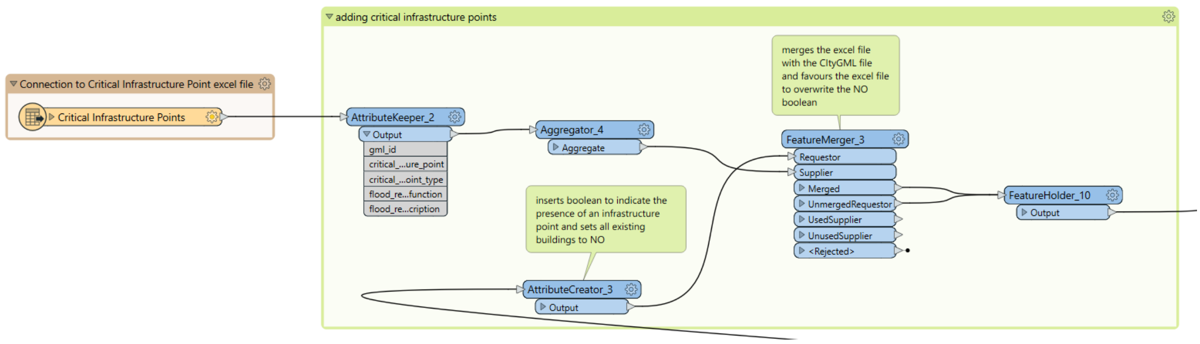


Figure 60. FME workbench for adding critical infrastructure points.

4.2.3 Adding additional built environment objects to the CityGML file

The built environment does not only contain buildings but also other fixed objects like bridges (of which none were modelled in the study area), vegetation objects, and city furniture such as garbage bins, bicycle racks, charging stations, parking meters, and lampposts. These additional objects were also modelled and stored in CityGML file format by the municipality of Rotterdam and are downloadable through their 3D viewer.

Solitary vegetation objects

Other objects that can be added to the 3D model are solitary vegetation objects – or in other words, trees. The information on and geometries of the trees in a certain neighbourhood are provided in two separate files; one containing the crowns of the trees and the other one containing all the trunks of the trees. After importing both the tree-crown and -trunk files of a neighbourhood as readers into the FME script and running them to have a look at the data of the CityGML files, it becomes clear that the files contain errors which is normally the default. However, in this case, these errors could have been avoided as they occur when the files are validated which was not done before they were made public. Looking at the error messages and comparing them to the code (opened in Visual Studio Code), shows that the errors are related to the schema of the CityGML file and are recursive in each tree file that was downloaded. Each file contains trees that have empty value strings on either a tree's crown diameter or trunk diameter. In the case of the figure below, the empty value is for the attribute crown diameter.

```
</gen:stringAttribute>
<veg:height uom="m">8</veg:height>
<veg:trunkDiameter uom="cm">100</veg:trunkDiameter>
<veg:crownDiameter uom="m"></veg:crownDiameter>
```

Figure 61. Empty value string for the attribute crown diameter which leads to errors during validation.

Rectifying these errors manually (more than 23.000 errors combined) is not efficient and also contradictory to the building industry's need to automate processes. Therefore, these errors are solved by manipulating the content of the files in one single FME workbench.

To solve the error messages in the tree files, first, the reader validation is turned off. This allows the writer to run without terminating the process. Then, all attributes are filtered by either the crown diameter or the trunk diameter on their possible values status followed by the removal of the crown and trunk diameter attributes that were identified as having an empty value.

Validating the newly manipulated CityGML file by adding the new file as a reader and turning on the validation parameter shows that the errors are still not resolved. Looking at the errors in the code a second time reveals that while the attributes for crown diameter and trunk diameter were removed where necessary, a 'slash' remained, leading to the same error message (see Figure 62 for the slash in question). The easiest way to remove this slash is to also remove the crown or trunk diameter unit for the crown and trunk diameter attributes that have an empty string value. Removing these attributes is of no consequence for the remaining data as there is no numerical value to go with the unit anyway.

```
<gen:stringAttribute name="tree_part">
    <gen:value>stam</gen:value>
</gen:stringAttribute>
<veg:height uom="m">8</veg:height>
<veg:crownDiameter uom="m"/>
```

Figure 62. Redundant 'slash' that leads to an error message.

By simply adding the attribute for crown or trunk diameter unit to the attribute remover transformers, most errors regarding empty string values are resolved.

A handful of errors, however, remain. While the information on tree crowns and tree trunks is divided over the two different files, both files still contain information that is related to the former errors. Therefore, an additional attribute filter, as well as an attribute remover, is added to each file, removing the opposite attributes with empty string values. This last step will remove all errors from the tree files.

The final step that is needed to create a single enriched tree file of a neighbourhood, is done by simply connecting the outputs from the two files to one writer which 'writes' a new CityGML file including all the required information.

Validating the newly created CityGML files indeed shows that after running the FME workbench depicted in Figure 63, all errors are removed and the two tree files of a neighbourhood (in this case Hillegersberg Noord) are combined into one. The data is also checked visually by opening the FME Inspector (see Figure 64 for the visual check).

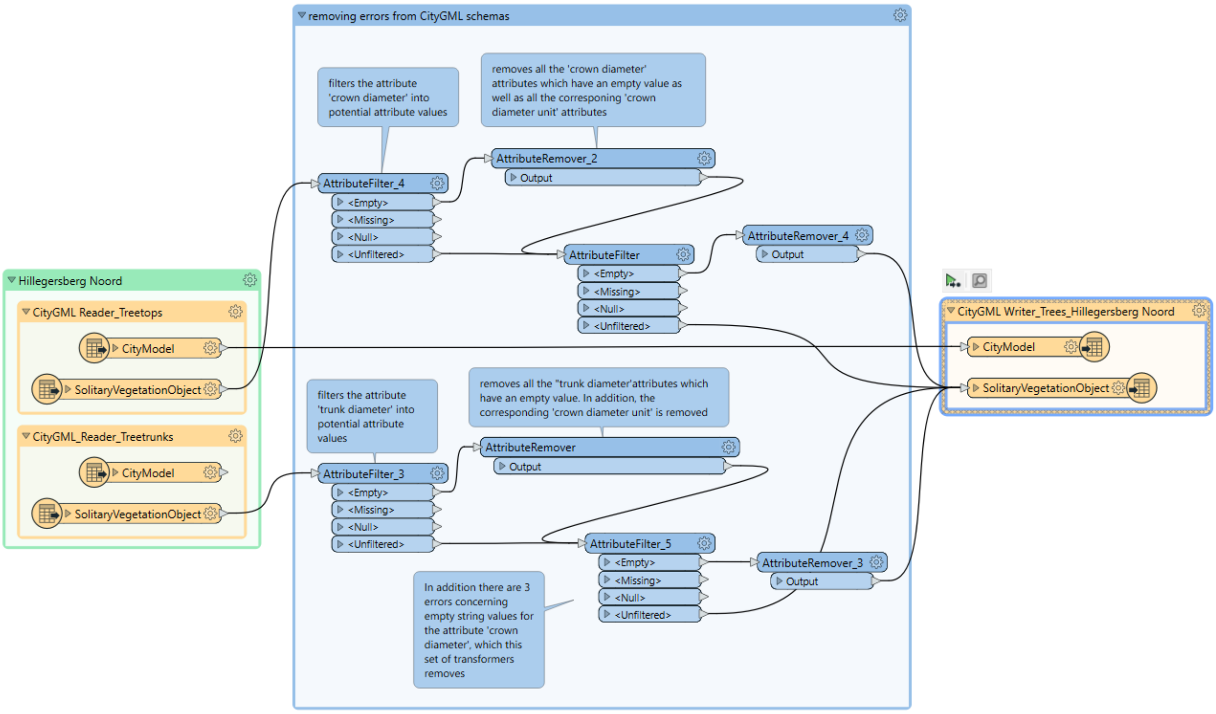


Figure 63. FME workbench for manipulating tree file of Hillegersberg Noord.

As Hillegersberg Noord is not the only neighbourhood within the study area, the FME workbench has to be re-run another 9 times with the readers and writer corresponding to the remaining 9 neighbourhoods (see Appendix F for the complete FME workbench).

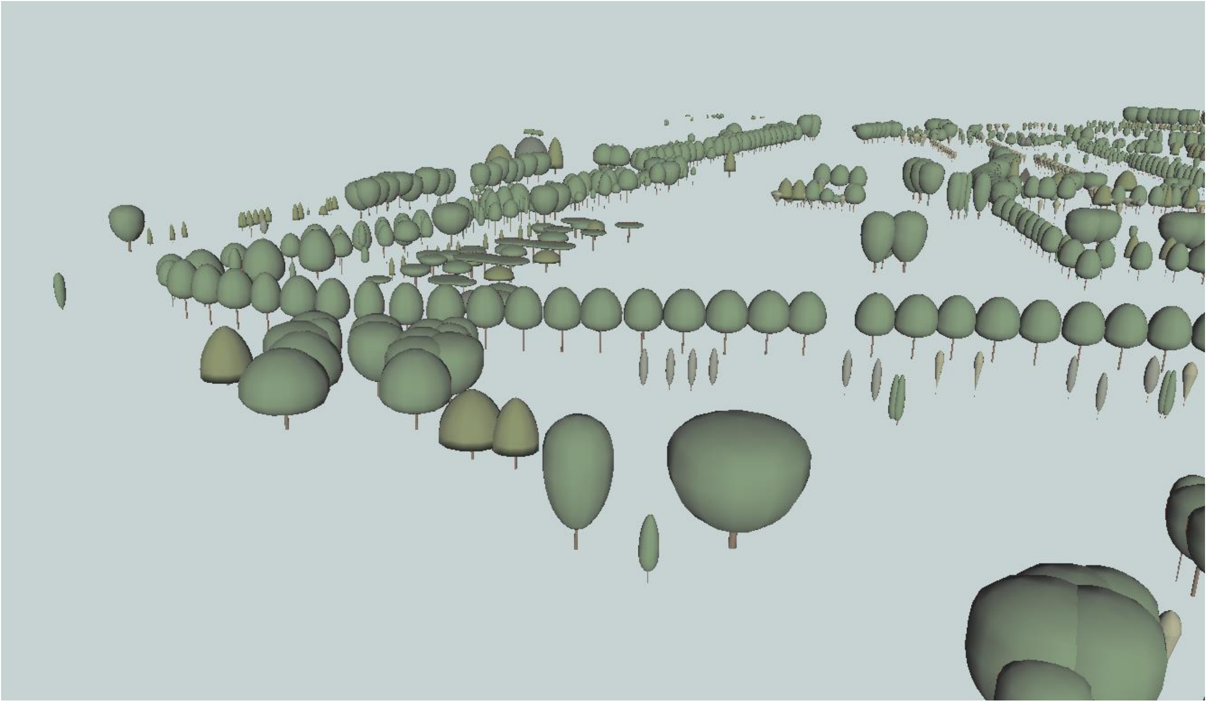


Figure 64. Enriched trees of Hillegersberg Noord in the FME Inspector.

When trying to load the tree files into the 3DCityDB together, however, the import failed due to an XLink reference that cannot be resolved. Figure 65 shows an example of such an XLink reference error message. To resolve this problem, each tree file of a neighbourhood is loaded into a new, separate schema bearing the same name as the corresponding neighbourhood. Later on, the now separated tree files will be brought together in QGIS using the 3DCityDB-Loader where the XLink reference errors are ignored.

```
[13:40:13 ERROR] Failed to resolve XLink reference '#fme-gen-4147706b-a01a-40c4-8a58-2a563b4f216b'.
```

Figure 65. Example of XLink reference error received from the Importer/Exporter tool when importing all tree files.

City Furniture

Downloading the required city furniture files from Rotterdam 3D is a more difficult process than downloading the solitary vegetation object files. While the tree files can be downloaded per neighbourhood using an order format, the city furniture files have to be downloaded using a download function built into the 3D viewer. This download function lets the user draw an area on a map of Rotterdam which can then be downloaded. This downloadable area is defined by a bounding box which can also be adjusted manually. To ensure accuracy, the bounding box coordinates are edited, rather than drawn. Unfortunately, the downloadable area cannot be greater than 2.000.000 square meters. However, the study area considered in this research is much greater. Therefore, the study area is divided into downloadable tiles resulting in 21 tiles/files. The bounding boxes used for each of the 21 tiles can be found in Appendix C. Among others, the appearances of the features can also be downloaded alongside the city furniture files. However, these files are then not valid because the name of the JPEGs representing the different appearances have spaces. At this point, either the names of the JPEG files and the links to these files in the CityGML code have to be changed manually (which counteracts the need to automate processes) or new files are downloaded that include the generic attributes of the city furniture but not their appearance. The latter option was chosen as appearance is an addition to the 3D city model that is outside of the scope of this research.

The next step would be to utilize FME Workbench and combine the 21 files covering the study area and filter the data by its neighbourhood. This way, the information on city furniture could be written in a single CityGML file per neighbourhood and information from neighbourhoods that fall within the bounding box of the study area but outside of the polygon of the study area, would be excluded. As the above research has shown so far though, manipulating the city furniture files does not come without additional obstacles. After re-downloading the 21 City Furniture files, a new set of error messages arise when trying to combine the 21 files which turn out to be a much greater problem to solve. Each file has a unique gml_id for an object (eg a street lamp) which is then duplicated so the object only has to be modelled once. These 'links' to the original object are called XLink references. Each new file defines the object anew with a unique gml_id. To be able to combine the files, the unique gml_ids should be different from each other which in this case, they are not. If a single city furniture file of Rotterdam could be downloaded or if the gml_id's were indeed unique and not being recycled, this problem would not exist. Trying to import the files into 3DCityDB without sorting them by neighbourhood shows that the 3DCityDB importer is also unable to resolve the XLink reference errors. The newest version of the Importer/Exporter, however, is supposed to resolve XLink problems. After installing the newest version, and setting up the 3DCityDB again, the Importer/Exporter tool is able to resolve the error when importing not more than 3 files. As there are more than 3 files, the 21 files are combined into 7 CityGML files each including 3 original files. These combined files are then sorted by neighbourhoods and all the neighbourhoods outside the study area are excluded. Figure 66 shows the FME Workbench that was used to do so. Finally, the remaining 7 files are imported into the citydb schema.

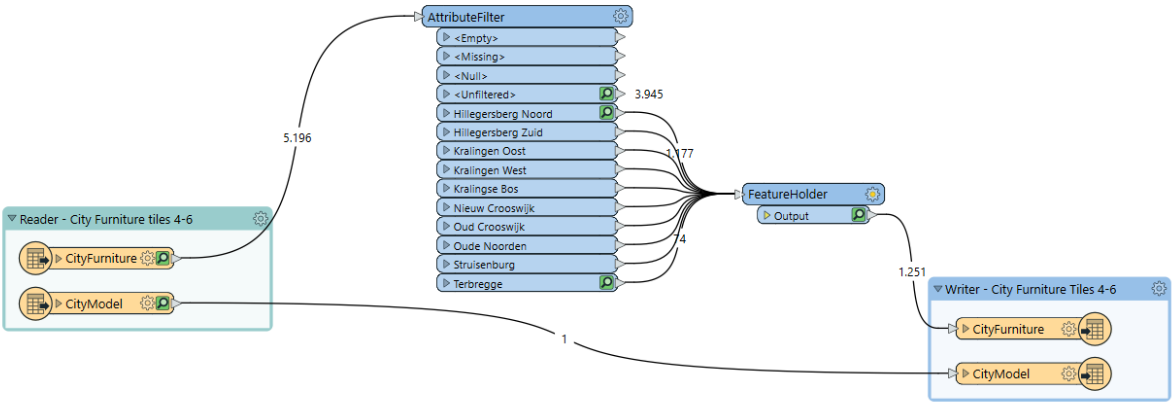


Figure 66. FME workbench for sorting the semi-combined city furniture files by neighbourhoods.

4.3 Flood simulation connection

The next step in developing a semantic 3D city flood model is to connect the developed semantic 3D city model of Rotterdam with a flood simulation. As no publicly accessible and sophisticated flood simulation model exists that can be connected to the 3D city model, two outputs of the hydrodynamic simulation model 'Rainfall Overlay' that Deltares made public in the Klimaateffectatlas (n.d.) are utilized. The first output layer is a flood inundation map that would be a result of a heavy rainfall during which 70mm of water will fall within 2 hours (a scenario that is expected to occur every 100 years), whereas the second output layer considers an even more intense rainfall of 140mm per 2 hours (which is expected to occur every 1000 years).

Figure 67. Flood inundation layers [TIF] representing a rainfall intensity of 70mm per 2 hours (left) and of 140mm per 2 hours (right).

There are several ways to connect these two 2D output layers with the semantic 3D city model to then run queries to determine the Flood Resilience Score of the study area. The first option would be to connect the 3D model with the output using FME and determining all the locations where the output layer would intersect the geometries of the 3D model. Another way would be by making use of the 3DCityDB-Loader. This loader is a QGIS plug-in that connects the 3D city data within the 3DCityDB to QGIS. This way, the 3D data can be loaded into QGIS and at the same time, changes made to the data in QGIS are sent back to the 3DCityDB.

After downloading and setting up the plug-in, a connection is created to the database 'my3DCityDB' by creating a new schema in my3DCityDB, installing a new user, and then creating a connection to the correct database. First, the citydb schema is connected, a layer is created and refreshed, and all buildings within the study area are loaded into a layer in QGIS followed by all city furniture objects which are loaded into a separate layer. Figures 68 and 69 depict the two different layers in the QGIS interface.

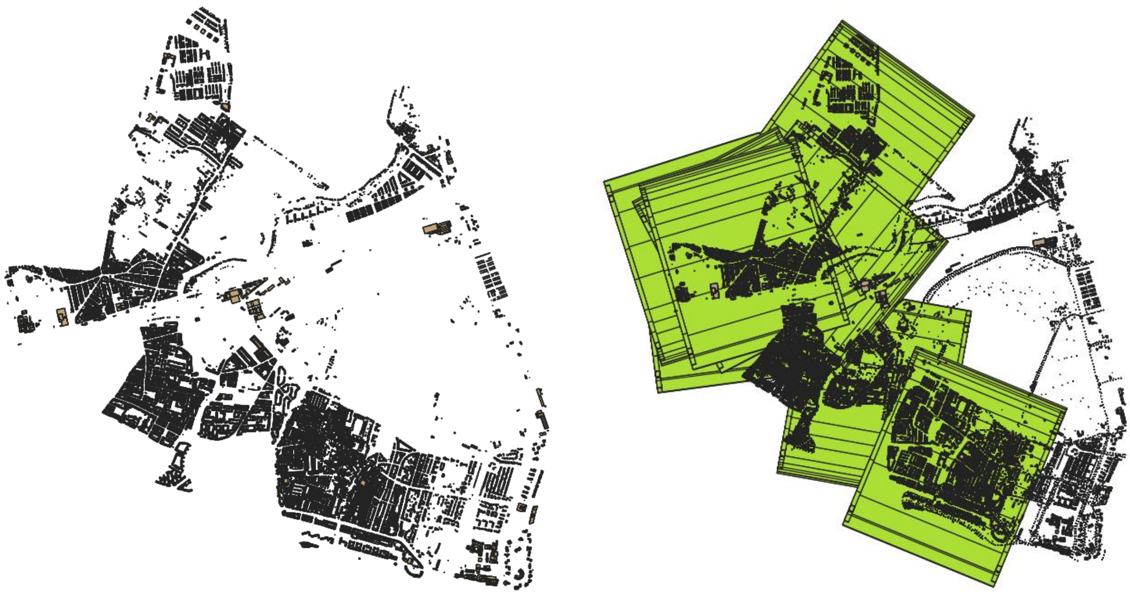


Figure 68 and 69. The building layer (left) and the city furniture layer (right) in QGIS.

It becomes clear from Figure 69 that 9 of the bike racks are massively out of scale, an error in the city furniture files that was not discovered previously. The 9 city objects are quickly removed in QGIS which also removes them in the 3DCityDB. The resulting city furniture layer can be seen in Figure 70.

Figures 70 and 71. The adjusted city furniture layer (left) and the vegetation layer (right) in QGIS.

Now that all the required features from the citydb schema are imported, the loader is used to connect QGIS to each of the 10 neighbourhood schemas and import the vegetation layers into QGIS. Figure 71 depicts the vegetation layer.

Using the QGIS plug-in 'Qgis2threejs Exporter' the loaded layers are visualized in 3D (see Figure 72).

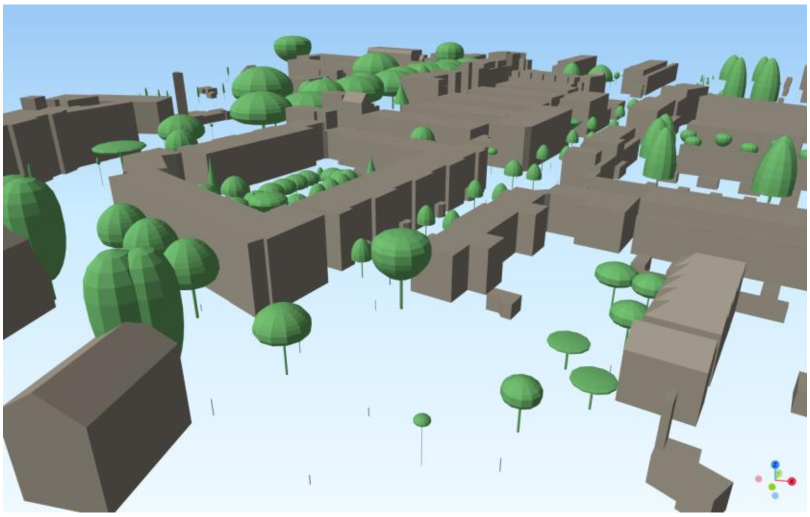


Figure 72. 3D visualization of the 3D city model in Qgis2threejs. Left: Excerpt of the model.

To connect the 3D city model with the flood inundation maps, the two TIF files are simply loaded into QGIS as raster layers. However, as the 3D city model is classified as a vector layer, the flood inundation maps have to be converted from raster layers to vector layers. The result is a layer with cells numbered from 1 to 5 and representing a different inundation depth. Because the inundation depth is not taken into account during this research, the 'flooded' cells 1 to 4 are kept but no distinction between them is made.

While the cells with a value of 5 represent areas that are not flooded, the conversion did give them a value. To only keep the 'flooded' cells, the Query Builder of QGIS is used to only consider cells with a value lower than 5 as suitable. A part of the resulting vector layer is shown in Figure 73.

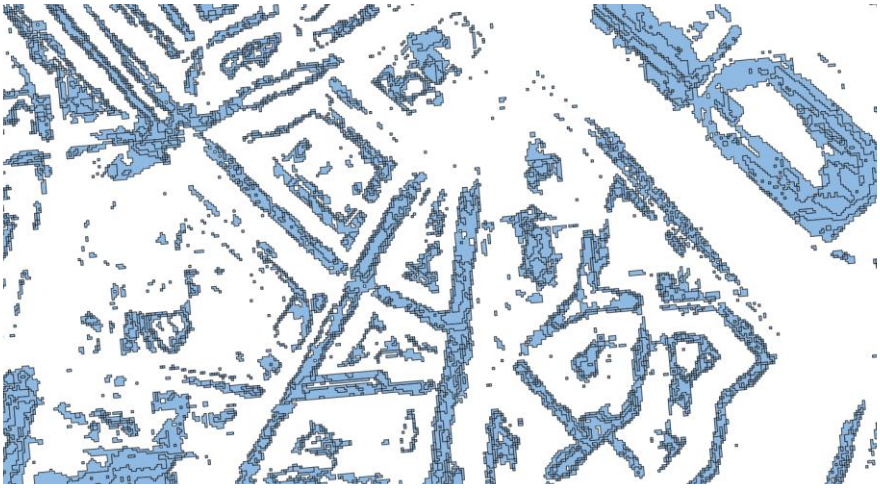


Figure 73. Adjusted vector layer of the flood inundation map resulting from a rainfall intensity of 70mm per 2 hours.

All layers are then overlayed to visually validate the connection. The 3D city flood model can be visualized in either the 2D interface of QGIS (see Figure 74) or in the Qgis2threejs Exporter (see Figure 75).

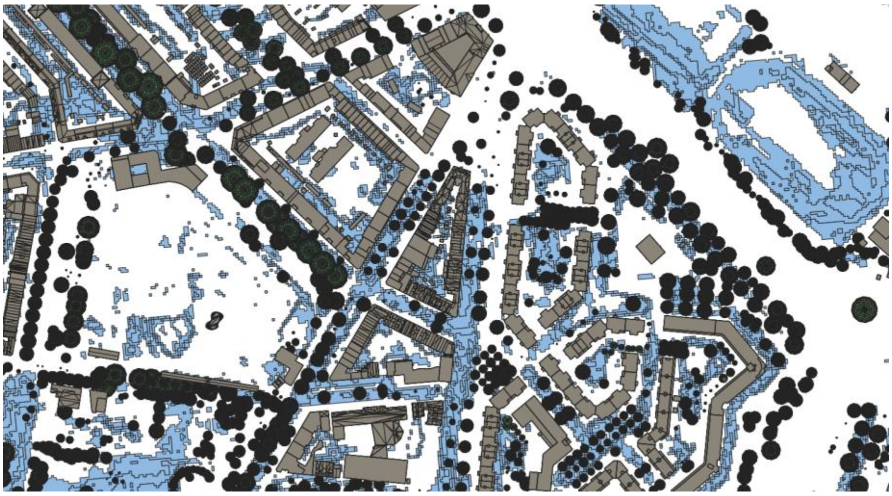


Figure 74. Cut-out of the 3D city flood model in QGIS.

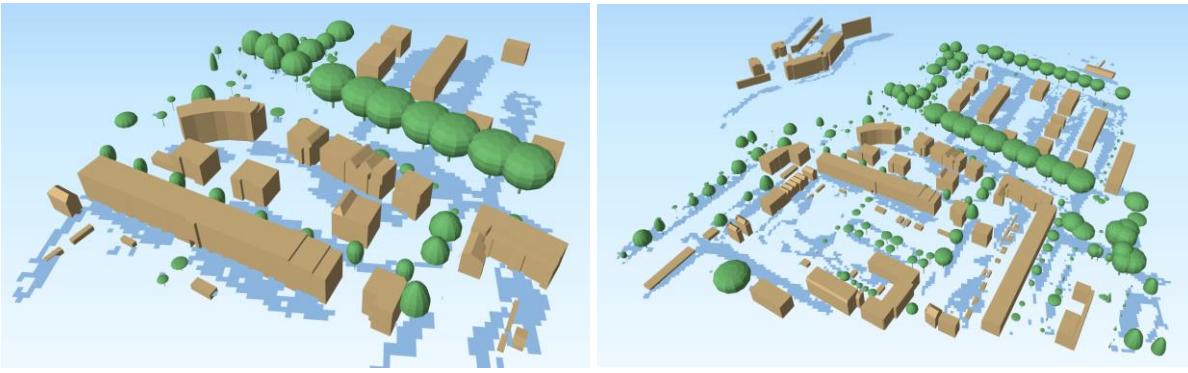


Figure 75. Cut-outs of the 3D city flood model in the Qgis2threejs Exporter.

4.4 Conclusion

In this chapter, a semantic 3D city flood model of Rotterdam was successfully developed. The model was created using open datasets and now has the potential to be utilized to evaluate the impact of a flood on a city.

The process of creating the semantic 3D model began with setting up the model including obtaining and validating 3D city data of Rotterdam. The CityGML files that store the 3D city building data were then enriched with additional building information and infrastructure points that play a critical role during floods. This information is later needed to evaluate the impact of the flood on buildings and households. Additionally, other fixed built environment objects such as trees, lamp posts and trash bins were added to the model. The process of enriching the 3D city model was tedious as it turned out that many of the files had validation and coding errors which first had to be resolved. To be able to connect the two flood scenarios and their flood inundation maps to the 3D city model, a connection was created between the 3DCityDB containing the 3D city data and QGIS. The flood layers were then imported into QGIS and the two flood scenarios alongside the 3D city model were visualized in QGIS.

Overall, this chapter has shown that it is indeed possible to develop a data-enriched 3D city model based on CityGML and connect flood simulation output to it which functions as a basis to later on better understand and prepare for the potential impacts of flooding on a city.

5. Evaluation of flood resilience

The following chapter describes how the required data for the Flood Resilience Score is collected using QGIS and how the data can be queried using several methods; PostgreSQL, a QGIS dashboard, and merging Excel files using Power Query. The best method is then further elaborated upon and the content of the Flood Resilience Score is clarified (Section 5.1). Afterward, the results of the Flood Resilience Score for the total study area as well as the scores of the most interesting neighbourhood are evaluated and compared to each other (Section 5.2).

Then, the potential of developing a spatial planning support tool for city planners, based on the semantic 3D city flood model, is evaluated. First, the process of changing the model in such a way that future environmental plans can be included when calculating the resilience of the study area, is elaborated upon in Section 5.3 and afterward, the results of the Flood Resilience Scores for the new environmental plan of Nieuw Kralingen are evaluated and compared to the scores of the total study area (Section 5.4).

5.1 Development of Flood Resilience Score

To develop the Flood Resilience Score (FReSco), data on the buildings that are flooded, and the buildings that are affected by the flood need to be queried in the form of a list containing all the buildings and their information before any score can be calculated. (In the case that a database model can be used instead of a file-based model, the list of buildings does not have to be imported into one file to do calculations as a script with multiple queries can handle the calculations better.)

This list should contain the BAG IDs of all objects, their addresses, their function, the number of households within the building, if the object is a critical infrastructure point and if so what kind as well as its flood resilience function, and their status in regard to the flood ('flooded', 'affected by flood' and/or 'within reach of dangerous infrastructure point'). Adding the three latter statuses as generic attributes to the CityGML files beforehand and editing them accordingly using the 3DCityDB-Loader would be a very efficient way to obtain the required information, however, batch editing generic attributes of selected objects using the Loader is not yet possible. Therefore, these attributes are later added to indicate which buildings are either flooded, affected by the flood, or within reach of dangerous flooded infrastructure points.

To find out which of the buildings are flooded, a simple spatial analysis is run in QGIS to select all buildings that intersect, touch, contain, overlap, or are within the flood layer (for the following examples, the flood inundation map that results from a heavy rainfall with an intensity of 70mm per 2 hours is used). The results of the spatial analysis are shown in Figure 76 where all the orange-coloured objects represent flooded buildings.

Figure 76. Visual representation of the flooded buildings (orange).

The next step is to locate the buildings that are directly as well as indirectly affected by the flood. To do so, first, all flooded vital infrastructure points are selected and saved. After inspecting a total of 4 vital infrastructure points, it becomes clear that all points are supermarkets. On average, the closest supermarket in Rotterdam is at a 500-meter distance from a residence (Compendium voor de Leefomgeving, 2022). Therefore, a buffer of 500 meters is created around the flooded supermarkets to see how many households will be indirectly affected by the flood by not being able to get groceries (see Figure 77).

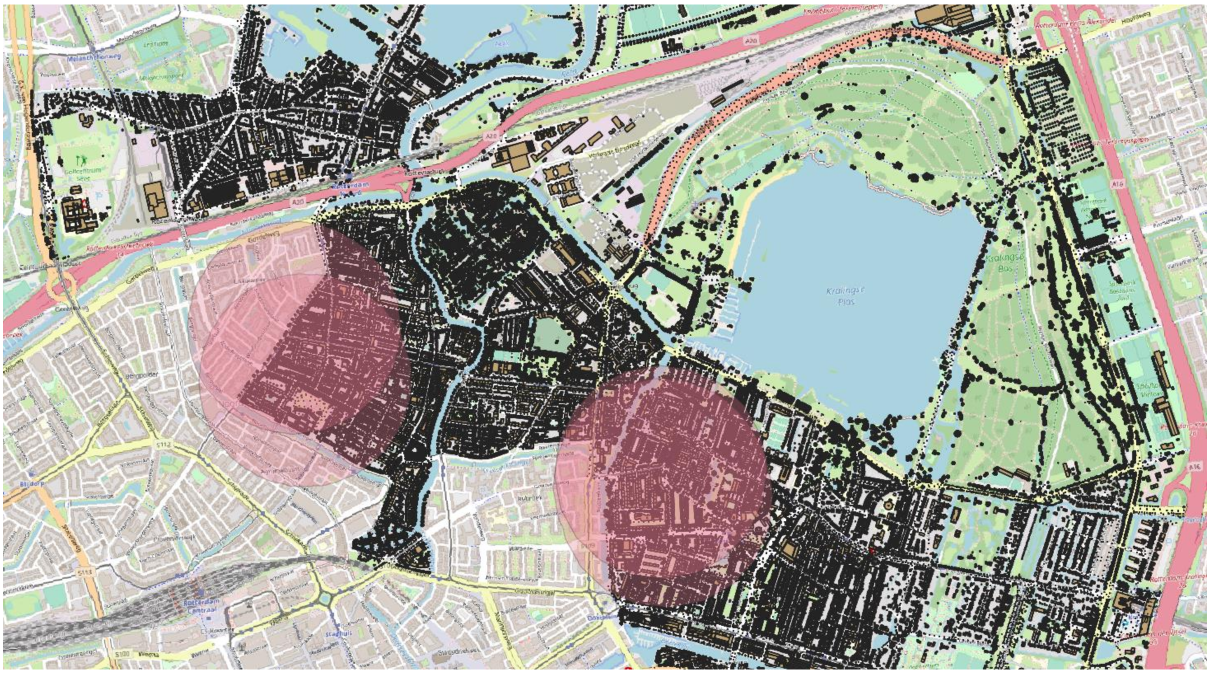


Figure 77. 500-meter buffers around the flooded supermarkets in the study area.

Intermezzo: From Figure 77 it becomes clear that most of the study area seems to not have access to a supermarket within 500 meters which seems unreasonable for a city such as Rotterdam with a very high count of supermarkets. It can therefore be concluded that many supermarkets were not added to the critical infrastructure points list. If this is not the case though, the reach of the supermarkets should be much greater and more households are actually indirectly affected. At the same time, the current method does not leave room for inhabitants to do their groceries at a different supermarket which is not flooded and might still be within their 500-meter reach. Now every single building and their households are classified as affected even though they might not be. So the spatial analysis should actually have been conducted the other way around where only the amount of buildings and households are counted that are unable to reach a supermarket within 500 meters that is not flooded. Furthermore, some critical infrastructure points such as hospitals, police stations, and fire stations have a much greater impact on the city's inhabitants when they are flooded then supermarkets. End of the intermezzo.

All buildings that are within the expected reach of the supermarkets are then queried and the already flooded buildings are added to create the directly and indirectly affected building layer of which an excerpt can be seen in Figure 78.

Figure 78. Visual representation of the directly (orange) and indirectly (red) affected, but not flooded buildings.

An overview of all flooded vulnerable infrastructure points is also created to be used by, for example, first responders so they know which buildings and inherently the people residing in them should be prioritized during an extreme flood event. Figure 79 shows the spatial analysis that was used to select all vulnerable infrastructure points within the study and Figure 80 depicts the result of this analysis.

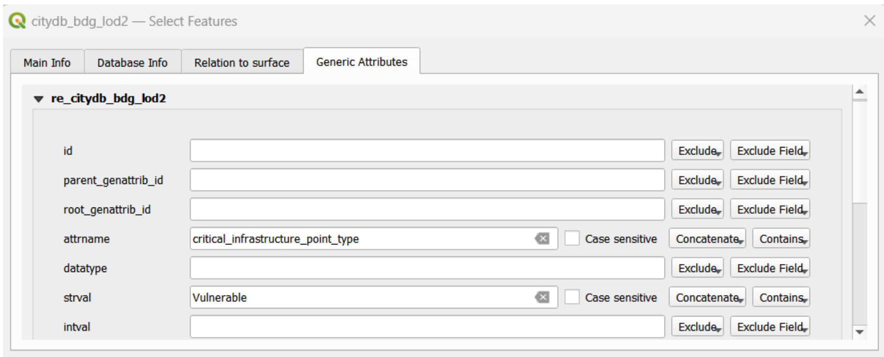


Figure 79. Spatial analysis to select all vulnerable infrastructure points within the study area.

Figure 80. Visual representation of the vulnerable flooded infrastructure points (lilac).

Finally, a layer including all dangerous flooded infrastructure points should be generated, however, there are no dangerous infrastructure points within the study area so the layer will not be generated.

After creating all required layers, the BAG IDs of each layer are exported to excel.

At this point, there are different options that can be used to further query the data and which were explored and are described below.

The first method makes use of PostgresSQL and its programming language PL/pgSQL to query the required data. But first, the exported excel files are added as readers to the FME workbench and then connected to the CityGML files to add the generic attributes 'flooded', 'affected_by_flood', and 'within_reach_of_dangerous_infrastructure_points' and if the situation is 'TRUE' or 'FALSE' for each object. The now incomplete content within the schema is fully deleted and the newly generated CityGML files are imported. Now, the PostgreSQL environment allows the user to run different queries. Some query examples are depicted in Figures 81 to 83.

```sql
SELECT DISTINCT test.cityobject.gmlid
FROM test.cityobject_genericattrib
JOIN test.cityobject
ON cityobject_genericattrib.cityobject_id=cityobject.id
WHERE attrname = 'flooded' AND strval = 'TRUE';
```

Figure 81. Query to collect BAG IDs of flooded buildings.

```sql
SELECT
-- all attributes from the cityobject_generic attribute table
attrname, strval, cityobject_id,
-- all attributes from the cityobject table
gmlid
-- all attributes from the objectclass table

FROM test.cityobject_genericattrib
JOIN test.cityobject
ON cityobject_genericattrib.cityobject_id=cityobject.id

WHERE attrname = 'flooded' AND strval = 'TRUE'
;
```

Figure 82. Query to collect the BAG IDs and generic attributes of flooded buildings.

```sql
SELECT
attrname, strval, intval
FROM test.cityobject_genericattrib
WHERE cityobject_genericattrib.cityobject_id = '5519';

SELECT
-- all attributes from the cityobject_generic attribute table
attrname, intval, test.cityobject.gmlid

FROM test.cityobject_genericattrib
JOIN test.cityobject
ON cityobject_genericattrib.cityobject_id=cityobject.id

WHERE cityobject_id in (
    SELECT cityobject.id

    FROM test.cityobject_genericattrib
    JOIN test.cityobject
    ON cityobject_genericattrib.cityobject_id=cityobject.id

    WHERE attrname = 'flooded' AND strval = 'TRUE'
)
AND attrname = '_households_per_building'
;
```

Figure 83. Query to calculate the number of 'flooded' households.

The reason why this method is not chosen in the end has to do with the way the tables in the database are joined and the way that the generic attributes are stored within the tables which makes it nearly impossible to obtain all the data required.

The dashboard created using the QGIS plugin 'QGIS_Dashboard'[3] that is depicted in Figure 84 creates a simpler overview of the data available in QGIS. While the creation of the dashboard is easier than the former SQL query method, the data available in QGIS is far from complete. The dashboard makes it possible to depict the total number of (flooded and affected) buildings within the study area, and the total number of vital and vulnerable flooded infrastructure points, however, neither the addresses of the (flooded

[3] https://github.com/luisCartoGeo/QGIS_Dashboard

or affected) buildings can be displayed, nor the number of (flooded or affected) households. At the same time, the QGIS dashboard does not allow the user to calculate a score using the available number. Instead, this would require an additional script to calculate the Flood Resilience Score.

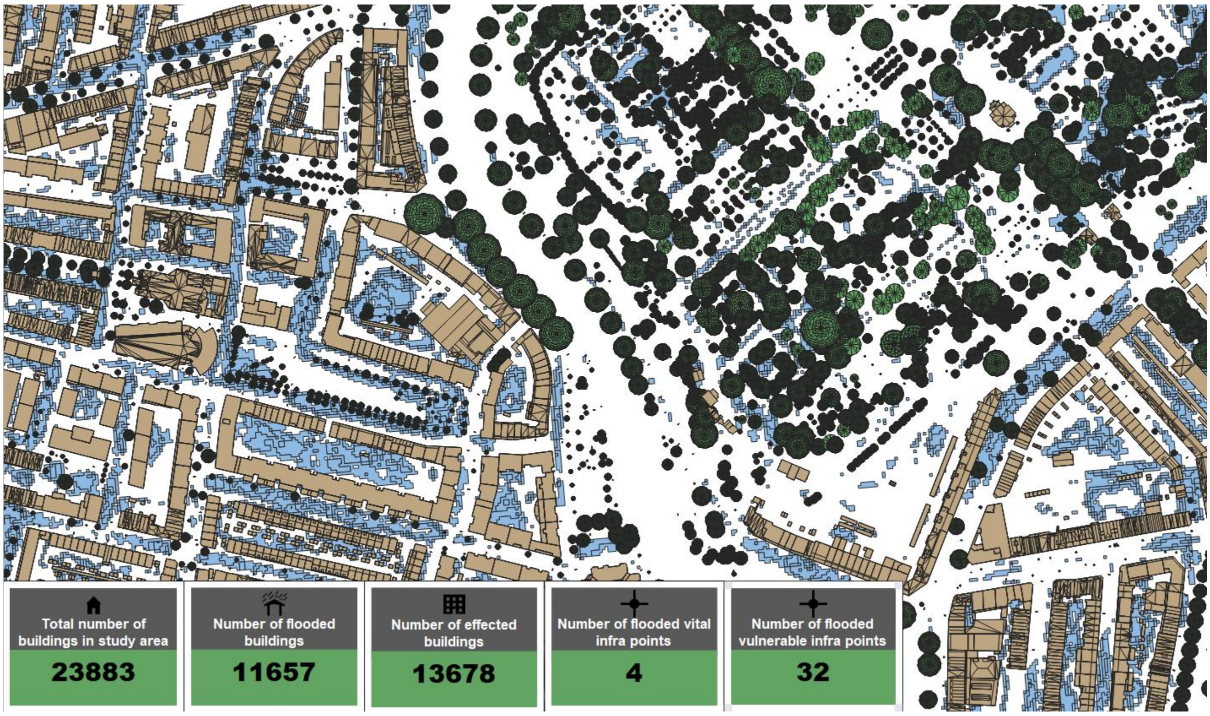


Figure 84. QGIS dashboard.

Another, easier but also more complete way to query and combine the remaining data is by exporting the required building data from the Importer/Exporter tool into an Excel document and merging it with the Excel files that were exported from QGIS. The exporter tool resolves the former problem of displaying generic attributes in list-form and allows the user to structure the Excel file and its columns according to the requirements of the research. Figure 85 shows an extract of the exported Excel file including all buildings in the study area.

	A	B	C	D	E	F	G	H	I	J
1	GMLID	street	house_num	neighbourhood	building_function	_households_per_building	critical_infrastructure_point	flooded	affected_by_flood	within_reach_of_dangerous_infrastructure_point
2	BAG_0599100010036436			Hillegersberg Noord			No	FALSE	FALSE	FALSE
3	BAG_0599100010070040			Hillegersberg Noord			No	FALSE	FALSE	FALSE
4	BAG_0599100010073342			Hillegersberg Noord			No	TRUE	TRUE	FALSE
5	BAG_0599100000434351	Johan de Wittlaan	10	Hillegersberg Noord	woonfunctie	6	No	TRUE	TRUE	FALSE
6	BAG_0599100000217567	Plaswijcklaan	28	Hillegersberg Noord	woonfunctie	1	No	TRUE	TRUE	FALSE
7	BAG_0599100000110752	Bergse Plaslaan	3	Hillegersberg Noord	woonfunctie	1	No	TRUE	TRUE	FALSE
8	BAG_0599100000641589	Kerstant van den Bergelaan	49	Hillegersberg Noord	woonfunctie	1	No	FALSE	FALSE	FALSE
9	BAG_0599100010003822			Hillegersberg Noord			No	FALSE	FALSE	FALSE
10	BAG_0599100000089179	Berglustlaan	78	Hillegersberg Noord	woonfunctie	1	No	FALSE	FALSE	FALSE
11	BAG_0599100000129940	Plasoord	23	Hillegersberg Noord	woonfunctie	1	No	FALSE	FALSE	FALSE
12	BAG_0599100010055922			Hillegersberg Noord			No	TRUE	TRUE	FALSE
13	BAG_0599100000436322	Straatweg	151	Hillegersberg Noord	woonfunctie	1	No	TRUE	TRUE	FALSE
14	BAG_0599100000602816	Adriaen van der Doeslaan	37-A - 37-B	Hillegersberg Noord	woonfunctie	5	No	TRUE	TRUE	FALSE
15	BAG_0599100000072878	Adriaen van der Doeslaan	16	Hillegersberg Noord	woonfunctie	1	No	FALSE	FALSE	FALSE

Figure 85. Excerpt of the exported Excel file from 3DCityDB containing all buildings and their information.

To merge the Excel files and join columns while overwriting one of the columns, the Power Query in Excel is used. After merging the files, the following data is collected;

- Total number of buildings in the study area,
- Total number of flooded buildings in the study area,
- Total number of directly and indirectly affected buildings in the study area,

- Total number of households in the study area,
- Total number of 'flooded' households in the study area,
- Total number of directly and indirectly affected households in the study area,
- Total number of vital infrastructure points in the study area,
- Total number of flooded vital infrastructure points in the study area,
- Total number of vulnerable infrastructure points in the study area,
- Total number of flooded vulnerable infrastructure points in the study area,
- Total number of dangerous infrastructure points in the study area, and
- Total number of flooded dangerous infrastructure points in the study area.

The collected data is then used to calculate the Flood Resilience Score in regard to buildings, households (of which there can be several once in a building), and vital, vulnerable, and dangerous infrastructure points using the following equation;

$$FReSco_a = 100 - \frac{100 * X_{f,a}}{X_a}$$

$FReSco_a$: Flood Resilience Score of study area a in % (0% means the study area has no flood resilience at all whereas 100% indicates great flood resilience)

X_f: number of buildings/households/infrastructures directly (and indirectly) affected by flood f in study area a

X_t: total number of buildings/households/infrastructures within the study area a

5.2 FReSco simulation results

Calculating the Flood Resilience Score regarding the number of affected households, buildings, and critical infrastructure points gives insight into how many objects are affected. But as there is no reference score from a similar but flood-resilient study area, it is difficult to know what an acceptable score is and draw a conclusion in regard to the flood resilience of Rotterdam. Therefore, the Flood Resilience Scores according to a rainfall of 70mm per 2 hours for the complete study area including all 10 neighbourhoods (which is described above) are used as a baseline. Then, the Flood Resilience Scores for each of the neighbourhoods are calculated to more precisely see where the flood problems lie within the city. The higher the score, the greater a city is equipped to withstand a flood whereas the lower the score the worse a city's flood resilience is.

Regarding buildings, the total study area scores 51,2% on flood resilience concerning flooded buildings and 42,7% when it comes to the directly as well as indirectly affected buildings. For households, the scores are 52,3% and 42,3%, respectively. These overall scores are used as a baseline for each neighbourhood to see which areas require intervention and which ones should be prioritized. From Figure 86 and Figure 87, it becomes clear that neighbourhoods such as Kralingen West and Oude Noorden score far below the baseline whereas Hillegersberg Noord and Kralingse Bos – neighbourhoods that both contain water reserves – score far above the average scores.

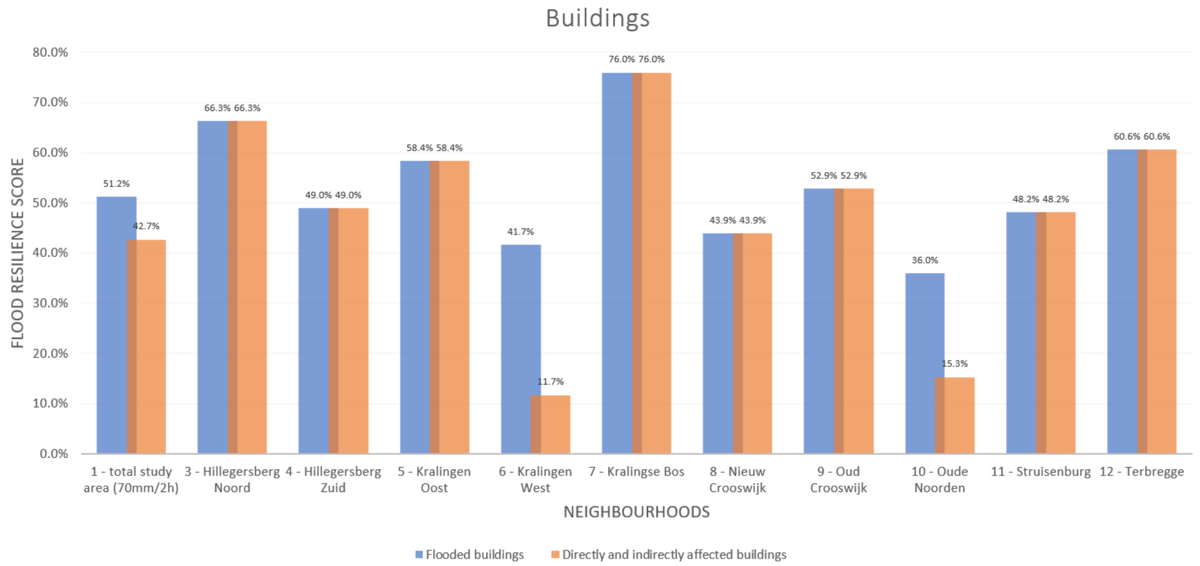


Figure 86. Bar diagram of Flood Resilience Scores for buildings.

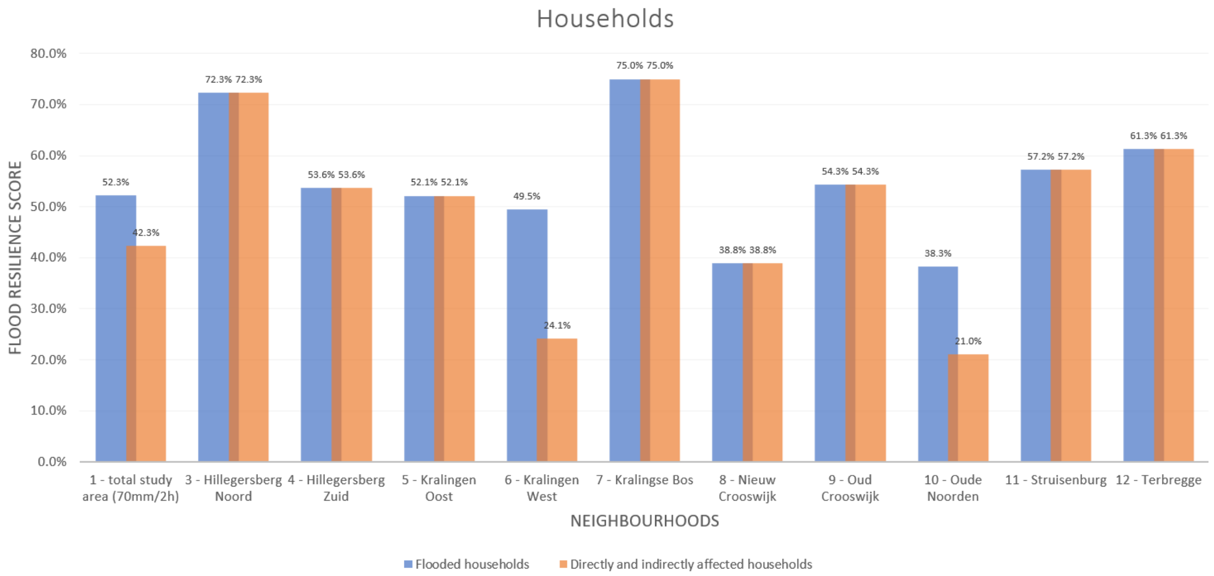
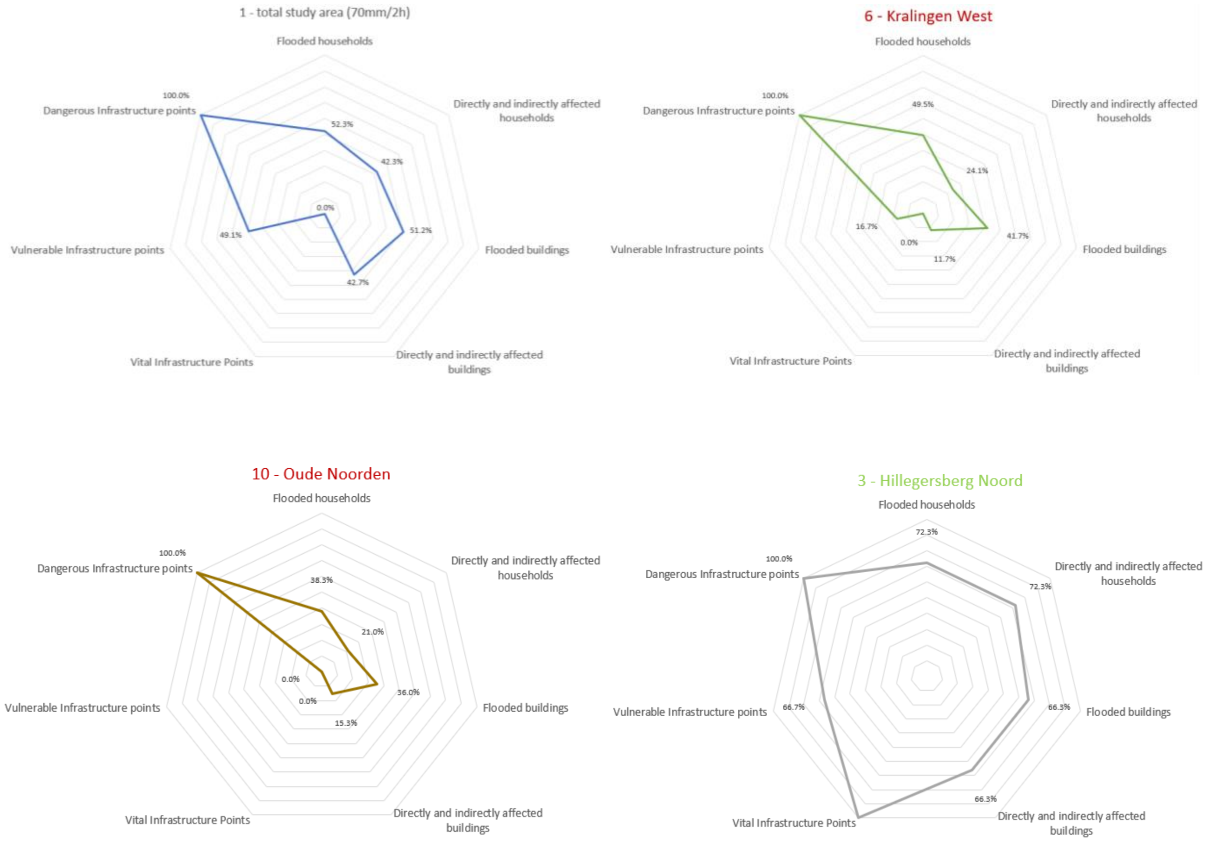


Figure 87. Bar diagram of Flood Resilience Scores for households.

Spider-diagrams of the before-highlighted neighbourhoods show a more detailed overview of the different Flood Resilience Scores (see Figures 88 to 91). While all neighbourhoods score high when it comes to dangerous infrastructure points as there are no such points in the study areas, nearly all neighbourhoods score low on vital infrastructure points. Among Figures 88 to 91 only Hillegersberg Noord scores 100% on the flood resilience of vital infrastructure points. The reason for this is the same as the one for the dangerous infrastructure points; no vital infrastructure points are located within Hillegersberg Noord. Investigating all vital infrastructure points (which are all supermarkets) in the total study area shows that of the 4 vital points, all four are flooded. As there are many more vulnerable infrastructure points within the total study area, 53 to be precise, the flood resilience results for these points are also more varied. The overview of the calculated data and the Flood Resilience Scores in Appendix H reveal that only Oud Crooswijk and Terbregge do not have any vulnerable infrastructure points leading to a score of 100% and that Hillegersberg Zuid and Oude Noorden do have vulnerable infrastructure points which are all flooded resulting in a score of 0%. Overall, it can be said that half of the vulnerable infrastructure points are flooded.

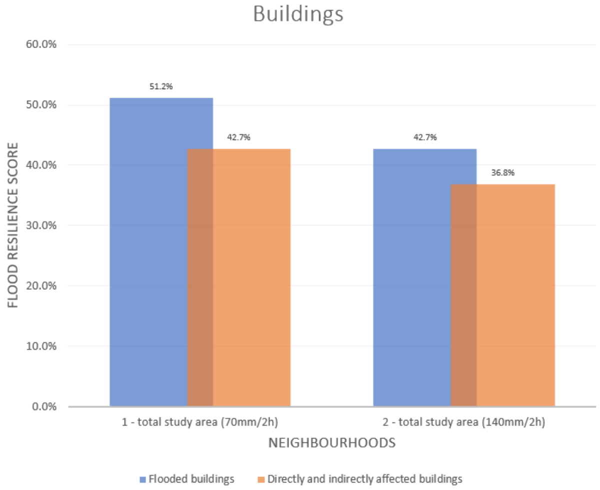
In regard to flooded households and directly and indirectly affected households, Hillegersberg Noord as well as Kralingse Bos score highest. The same is the case when looking at flooded as well as indirectly affected buildings. Figure 91 shows a spider diagram of all Flood Resilience Scores for Hillegersberg Noord. On the other side of the spectrum, Kralingen West and Oude Noorden can be found. Their respective spider diagrams depict a low resistance against floods. At the same time, both neighbourhoods also have the greatest difference between flooded and indirectly affected households and buildings as Figures 86 and 87 show. This reveals that these two neighbourhoods are most influenced by flooded vital infrastructures close by and in combination with their low performance, urban planners should direct their attention to them.



Figures 88 to 91. Spider-diagram of all Flood Resilience Scores for the total study area (top left), Kralingen West (top right), Oude Noorden (bottom left), and Hillegersberg Noord (bottom right), respectively.

As a rainfall can also vary in intensity, the Flood Resilience Scores of the total study area are compared to the scores of the more intense rainfall scenario of 140mm per 2 hours which is expected to occur every 1000 years. As expected, during a stronger rainfall, the number of buildings, households, and infrastructure points that are directly affected by the flood significantly increases (see Figures 92 and 93). However, the number of flooded vital infrastructure points remains the same (because there are no more supermarkets to be flooded). So the total amount of directly and indirectly affected buildings within the range of these supermarkets remain the same. This means that the amount of indirectly affected buildings (excluding the buildings that are flooded) actually becomes lower than during the less intense rainfall because the reach of the flooded supermarkets stays the same but the amount of directly flooded buildings within reach increases, leaving fewer buildings and households to be indirectly affected and more buildings and households being directly affected. This of course does not mean that the directly affected households do not face the same problem of not being able to go to the supermarket.

While the stronger rainfall is double the intensity of the first rainfall, the difference between the scores of the two rainfall scenarios is rather small in comparison, with less than a 10% difference. Furthermore, Figure 94 reveals that while the scores for the vital and dangerous infrastructure points for the rainfall scenarios are the same, the more intense rainfall leads to more vulnerable infrastructure points being flooded. Appendix H shows that indeed, during the stronger rainfall, 3 additional vulnerable infrastructure points are flooded.



Figures 92 and 93. Bar diagram of Flood Resilience Scores for buildings (left) and households (right) using two rainfall intensities.

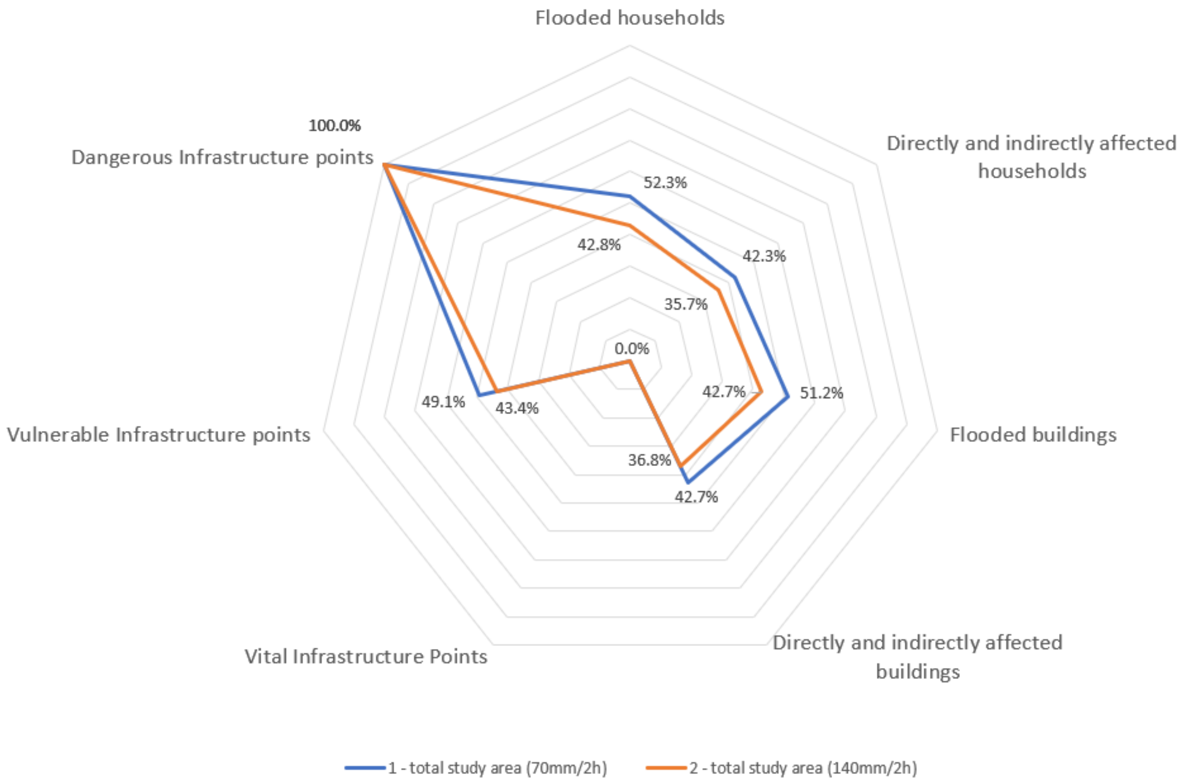


Figure 94. Spider-diagram of Flood Resilience Scores using two rainfall intensities.

5.3 Development of spatial planning support tool for city planners

To test the potential of developing a spatial planning support tool to evaluate the flood resilience of a new environmental plan, the urban planner would first either have to have access to a georeferenced shapefile of the plan or in the case of Nieuw Kralingen, where no shapefile is publicly accessible, first, a figure of the plan has to be inserted into QGIS. To make sure that the inserted figure aligns with the underlying Open Street Map layer, geo-reference points are used (see red dots in Figure 95).

Figure 95. Figure of urban plan for Nieuw Kralinge aligned with Open Street Map in QGIS.

Based on the urban plan of Nieuw Kralingen depicted in Figure 95, a new shapefile is created in QGIS including information on a temporary BAG ID - which have to be added as only already existing buildings receive a BAG ID - and the ground height at which the objects will be build. Tracing the outlines of the objects to draw polygons, creates a shapefile of Nieuw Kralingen (see Figure 96). To ascertain the ground heights of the area and include them as an attribute to the polygons, the AHN layer of the area is added to QGIS. Adding the surface level is required to later visualize the 3D model on the correct height.

Figures 96 and 97. Shapefile of Nieuw Kralingen (left) including the AHN of the area, where the increasing height of the surface area is indicated by the intensity of red (right).

The created shapefile is then imported as a reader into the FME workbench to be transformed to a CityGML file containing the 3D model of Nieuw Kralingen (the complete FME workbench can be found in Appendix G). Before creating LoD0 footprints out of the shapefile polygons and extruding the shapefiles to LoD1, new attributes are created including an attribute indicating the height of the buildings ('roof_z'). As there is no information on the expected height of the new buildings, the height of each building is set to 10 meters. Then, the model is offset to the current surface level of Nieuw Kralingen ('ground_z'). To change the polygons within the shapefile to LoD0 footprints, the polygons are first replaced by Faces and then turned into MultiSurfaces. Afterwards, the attributes that become geometry traits in CityGML are created and are then 'injected' into the geometries. To create a 3D model, the polygons are extruded to LoD1 according to the height of each building. The extrusion is then transformed into a CompositeSurface and from there into a BRepSolid followed by the creation and injection of the geometry traits. Figure 98 depicts the FME workbench that is used to change the 2D shapefile of Nieuw Kralingen into a 3D model.

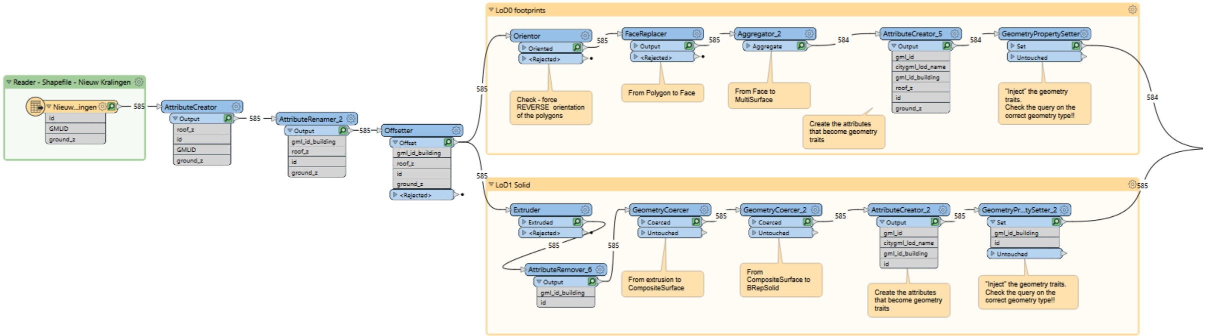


Figure 98. FME workbench of turning a 2D shapefile into a 3D model.

The newly created 3D model is inspected and checked in the FME Data Inspector as can be seen in Figure 99.

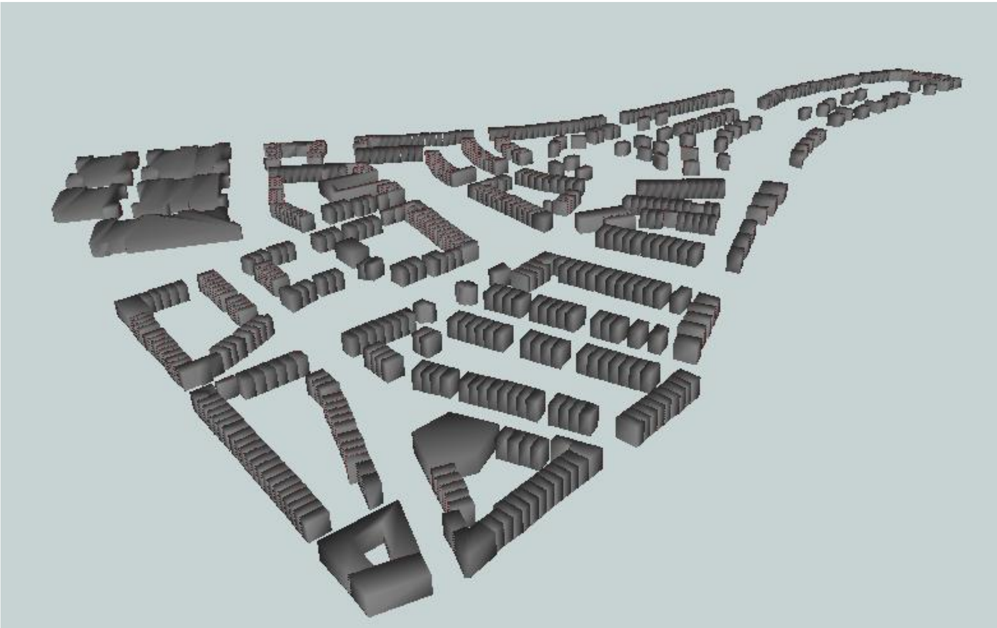


Figure 99. Resulting 3D model of Nieuw Kralingen in the FME Data Inspector.

Now that the geometries are manipulated so that they can be written into a CityGML file, the generic attributes that were also added to the CityGML building files in Section 4.2.1 are also added to the file of

Nieuw Kralingen. Figure 100 shows the generic attributes that were used to enrich the 3D model with additional data.

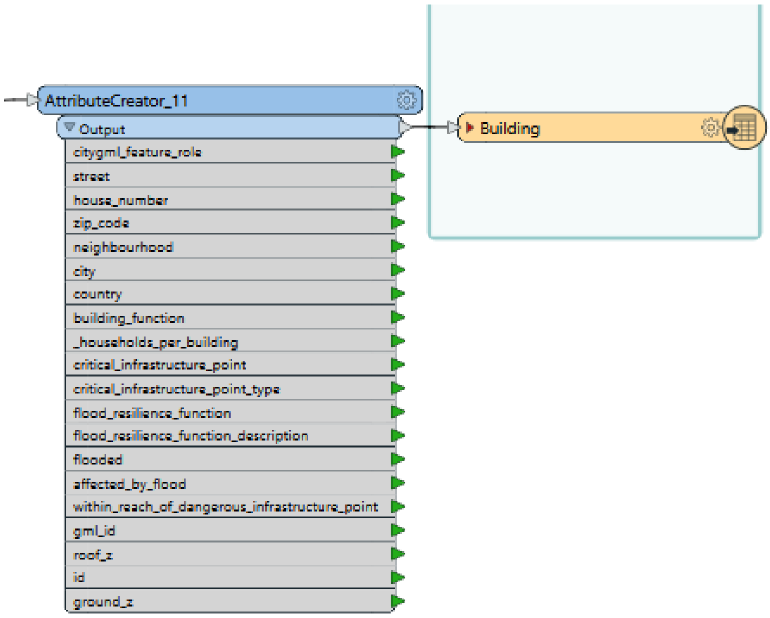


Figure 100. Enriching the 3D model with additional information.

According to Top010 (2022), Nieuw Kralingen will blend into the urban fabric of Rotterdam. However, services in the new neighbourhood itself will be scarce and residences are diverted to the surrounding neighbourhoods when they need any of these services. It is also expected that the new neighbourhood will not attract enough pupils to justify an additional elementary school. Furthermore, no supermarkets and retail stores will be added to Nieuw Kralingen. Services such as restaurants and cafes as well as offices and practices build alongside people's residences, however, are allowed in the neighbourhood. In other words, no critical infrastructure points will be located in Nieuw Kralingen and therefore no additional information on critical infrastructure points has to be added to the CityGML file. At the same time, all buildings within Nieuw Kralingen are therefore assumed to be residences, meaning that their building function is labelled as 'woonfunctie'.

The 800 residences/households that are to be built in Nieuw Kralingen (Gemeente Rotterdam, n.d.-b), are equally divided over the total number of objects (584 buildings) - which leads to 1,37 households per building – and then added to the CityGML file using the 'AttributeCreator' transformer in Figure 100.

After the urban planner has turned the shapefile of the new environmental plan into a CityGML file, the existing buildings that will be demolished to make room for Nieuw Kralingen are removed from the tool schema which was generated to test the new plans by using the 3DCityDB-Loader. By overlapping the Figure of the urban plan with the existing built environment, it becomes clear which of the buildings need to be 'demolished'.

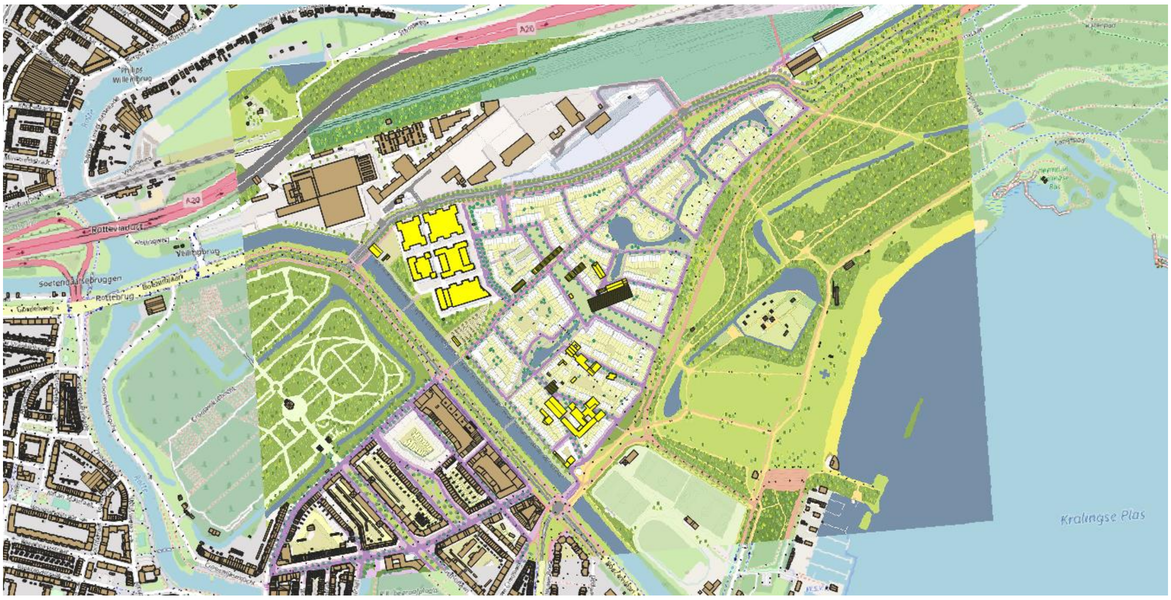


Figure 101. Removing the existing buildings (yellow) within Nieuw Kralingen from the schema.

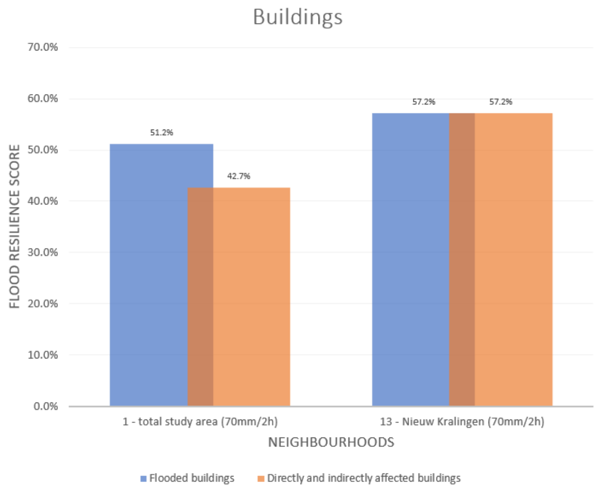
Next, the CityGML file of Nieuw Kralingen is imported into the 3DCityDB and the database layers in QGIS are refreshed to include the newly added buildings. Spatial analyses (as described in depth in Section 5.1) are conducted to uncover the location and number of flooded and indirectly affected buildings and of critical infrastructure points. Figure 102 shows the results of the spatial analysis that selects all objects that intersect the flood layer.

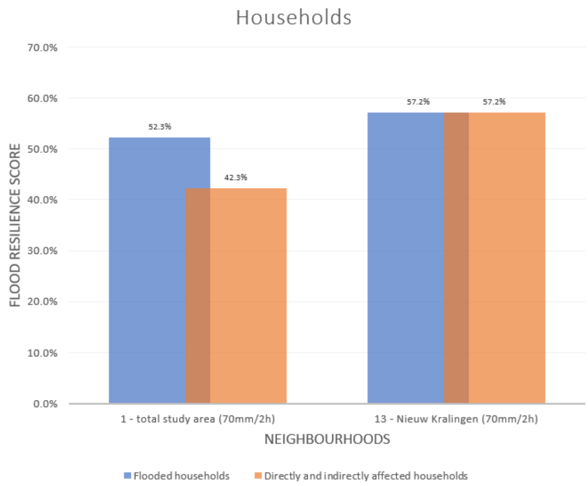
Figure 102. Flooded buildings (orange) in Nieuw Kralingen.

The building information of the flooded and affected buildings then has to be exported in Excel files, merged with the Excel file that was exported from the 3DCityDB, and the Flood Resilience Scores for Nieuw Kralingen are calculated.

5.4 Comparing the new urban plan to the original situation

Comparing the resilience scores to the baseline (the scores of the total study area) - while taking the limitation of the flood inundation map into consideration (Section 3.4) - reveals that Nieuw Kralingen scores higher than the average neighbourhood in Rotterdam on both the number of affected buildings and the number of affected households (see Figures 103 and 104). The results therefore imply that Nieuw Kralingen is more flood resilient than other areas even though the 'Kralingse Plas' and the 'Berge Voorplas' (large bodies of water) are located right next to it.





Figures 103 and 104. Bar diagram of Flood Resilience Scores for buildings (left) and households (right) of the total study area and Nieuw Kralingen.

The results of the Flood Resilience Scores for Nieuw Kralingen also show that both flooded as well as directly and indirectly affected buildings and households have the same score (see Appendix H and Figures 103 and 104). The reason for the same results is that no vital infrastructure points have an 'influence' on the new neighbourhood. As a matter of fact, not a single critical infrastructure point is located in the study area (which is in accordance to the description of Nieuw Kralingen according to the Municipality of Rotterdam (Gemeente Rotterdam, n.d.-b)) which is why the area scores 100% on flood resilience regarding vital, vulnerable, and dangerous infrastructure points as no points are flooded.

The spider diagram in Figure 105 even further supports the claim that Nieuw Kralingen is more flood resilient than the average neighbourhood in the study area, with the high score on infrastructure points leading to a 'greater surface'. However, as mentioned before, this score is not completely trustworthy as the complete absence of critical infrastructure points and especially the absence of vital facilities within or around the study area, has a negative impact on the quality of life and health of the citizens about to move into Nieuw Kralingen.

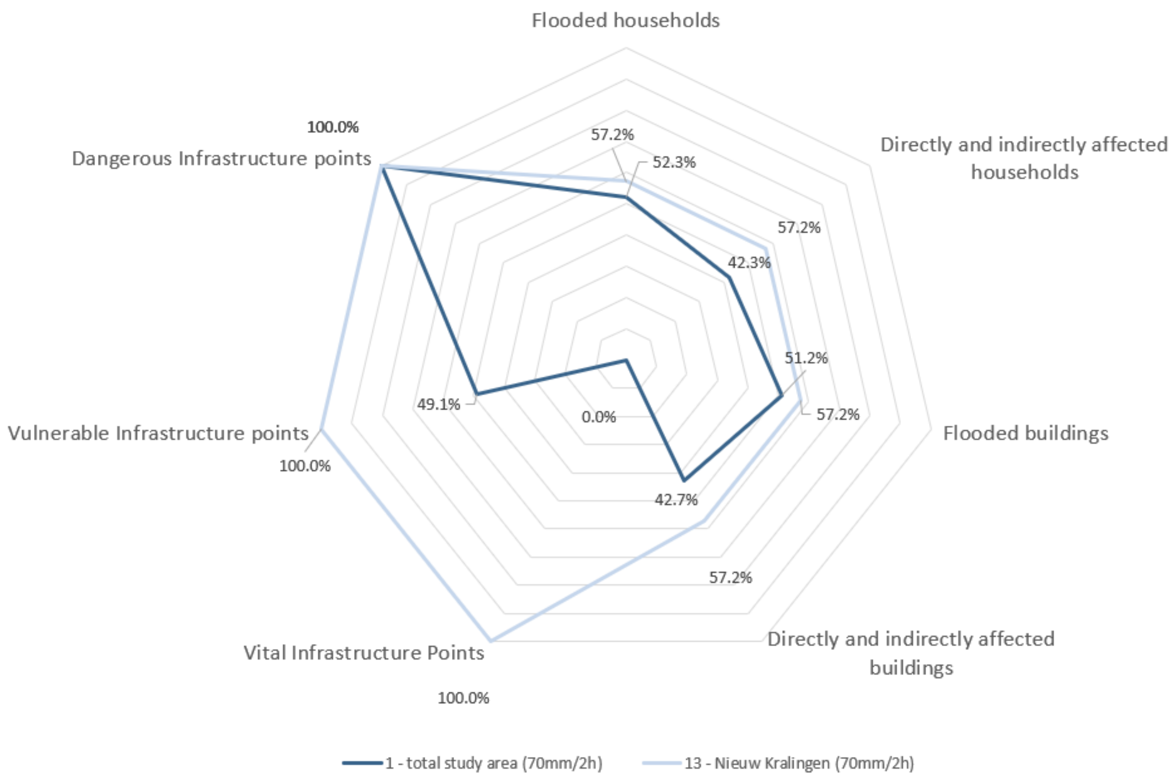


Figure 105. Spider-diagram of Flood Resilience Scores of the total study area and Nieuw Kralingen.

5.5 Conclusion

To summarize, this chapter focuses on the evaluation of the flood resilience of a city by developing a Flood Resilience Score after the connection between the semantic 3D city model and the results from a flood simulation model is established. First, the required data is collected using spatial analyses in QGIS and exported to an Excel file. From there, additional information that is only stored in the 3DCityDB is extracted from the database and the information is merged with the Excel file. The Flood Resilience Scores for the total study area under the two different flood scenarios are calculated followed by the calculations for the different neighbourhoods within the study area. Then, the different scores are compared to each other to find out which neighbourhoods are more or less flood resilient than the total study area.

Afterwards, the potential of developing a spatial planning support tool for city planners based on the semantic 3D city flood model is explored. First, the built environment of the 3D city model is changed to include a new environmental plan which involves creating a shapefile of the new environmental plan, transforming the 2D model to a 3D CityGML model, removing the buildings from the original 3D city model that are to be demolished, and importing the new CityGML file into the 3DCityDB. The spatial analyses are then repeated and the results of the Flood Resilience Scores for Nieuw Kralingen – the new environmental plan – are evaluated and compared to the scores of the total study area to find out if Nieuw Kralingen scores higher on flood resilience than the total study area, which it does.

6. Conclusion, Discussion, and Recommendation

6.1 Conclusion

In conclusion, this thesis has shown the value of using semantic 3D city models for assessing the current flood resilience of cities and the potential of using these models as spatial planning support tools to evaluate new environmental plans. The proposed process for developing these models, which involves the integration of various data sources, the application of semantic technologies, and the utilization of several software packages, has been demonstrated to be effective. The visual nature of the models can provide a clear and intuitive understanding of the spatial patterns and potential impacts of floods. Furthermore, the resulting model can provide valuable information about the effects of floods on the built environment and can be used to calculate a Flood Resilience Score which assesses the flood resilience of a city. The ability of the semantic 3D city flood model to visualize and analyse different planning scenarios can help urban planners to make better informed and more effective planning decisions for future environmental plans and their flood resilience.

However, despite their potential value, the process of creating these models is still largely a manual one, which can be time-consuming and prone to errors and which requires specialized expertise and equipment. Additionally, calculating a Flood Resilience Score for a city using open data can be difficult, but not necessarily impossible. The Flood Resilience Score can also change based on the information and data available or due to changes in the built environment, which highlights the importance of ensuring that the data used in these models is accurate and up-to-date.

Given the challenges and limitations of the current process for creating and using semantic 3D city flood models, there is a clear need for automation. Automating certain aspects of the process, such as data collection and processing, could significantly reduce the time and resources required to create these models. It could also help to improve the accuracy and reliability of the models by reducing the potential for human error. Automation could also make it easier to update and revise the models as new data becomes available, which would be particularly useful for calculating a city's Flood Resilience Score.

Overall, the use of semantic 3D city models for flood resilience analysis has the potential to support decision-making and planning efforts aimed at mitigating the effect of floods on cities but there is still work to be done in terms of improving the process of creating and using these models.

6.2 Discussion

Developing an open and semantic 3D city flood model is a fairly new research topic that only a very small number of researchers are engaged in as the literature review in Chapter 2 revealed. By basing the 3D city model on CityGML files, the number of researchers shrinks even further which is not a surprise as CityGML was only officially introduced in 2008, less than 15 years ago, and it is not widely used among city planners. Furthermore, the research functions as a proof of concept to see if and to what extent these 3D City models can be used. These facts inherently bring with them that there are still many aspects being discussed such as the applicability of these models, their scalability, and the standardization of these models as well as points for improvements and recommendations to other parties.

6.2.1. Differences between initial and final system architecture

Compared to the initial system architecture (see Figure 40 in Section 3.3), the final system architecture displayed in Figure 106 has undergone several changes throughout this research. While the development of the semantic 3D city model stayed mostly the same except for the critical infrastructure sources, the source of the flood inundation map changed from the hydrodynamic simulation model '3Di' to the hydrodynamic model 'Rainfall Overlay' developed by Tygron. The reason for the change was the fact that the latter has made results of the model in the form of flood inundation maps accessible to the public. At the same time, the flood maps were added to the 3D model by moving the work process to QGIS using the QGIS-plugin 3DCityDB-Loader instead of using a plug-in that connects the flood models of 3Di to the 3DCityDB which would have made the 3D city model more dynamic. In other words, the final research adds the flood output data to the 3D model instead of connecting the flood model to the 3D city model. While the visualization for the initial research was thought to be done using Cesium, the final visualization is taking place in QGIS and the Qgis2threejs Exporter. Finally, the Flood Resilience Score was meant to be calculated using the PostgreSQL database of the 3DCityDB, however, by changing to QGIS, the spatial analysis was now done in QGIS and by combining the results of these spatial analyses with data from the 3DCityDB, the Flood Resilience Score is calculated using Excel. Overall, these changes have simplified the process which makes it more accessible to its users such as urban planners. However, the process has also become a more manual one compared to the initial system architecture. From the start, the model was based on a file-based system rather than on a database system which makes the model static in the sense that the 3D database now has to be updated manually with many steps and an ETL procedure in between. A dynamic model, however, can be updated regularly or can send a request to the original database to receive the up-to-date data. For this thesis, a file-based model had to be chosen as the access to most of the original databases is restricted. However, for companies that own the databases or do have access to them, developing a dynamic model should be favoured over static models. The initial system architecture, however, included some automated features such as the connection of the hydrodynamic flood model to the 3D database through a plugin or the calculation of the Flood Resilience Score. In the end these automated features had to be changed to manual ones.

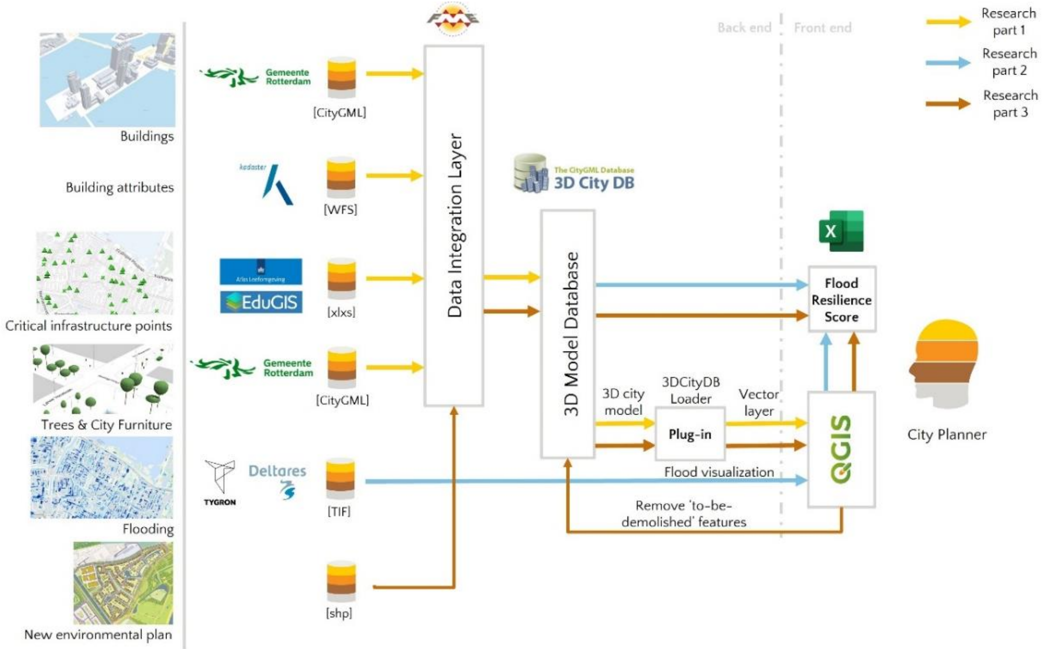


Figure 106. Final system architecture.

6.2.2 Digital Twin debate

As seen in the literature review, the debate on what are digital twins is ongoing. While some companies would call the semantic 3D city model that was developed for this research a(n urban) digital twin, most researchers agree that a digital twin should represent the situation of the real world now and should therefore include a time element. The developed 3D city model however does not (yet) include the potential of including real-time changes to the built environment over time as information on buildings is only updated when their construction is finalized and the BAG is updated. At the same time, a flood and its development over time could also be represented in the 3D city flood model. However, based on the chosen input data, this is not possible. By implementing real-time sensor data, BIM models, and storing historical data, the model could be turned into a detailed and dynamic representation of reality. The model would have the potential to go 'back in time' to evaluate past events and learn from them, while also being able to go 'into the future' - which the spatial planning decision tool tries to facilitate – to support urban planners in anticipating what is going to happen in the future and plan accordingly now. As the developed 3D model does not include most of these features yet, it cannot be called a digital twin. The model is however a first step towards a digital twin!

6.2.3 Scalability of 3D city models

To successfully complete the development of a semantic 3D city model based on CityGML files, the availability of geometrical and urban data is key. The research conducted revealed that while other countries struggle with the creation and publication of CityGML files that represent their built environment, the Netherlands is covered in its entirety by the 3D BAG, making the development of semantic 3D city models possible. On top of that, several municipalities within the Netherlands have created their own 3D city models, adding to the availability of data sets. Due to the availability of 3D city data, the developed model is, in theory, easily scalable to other cities or even the whole country to evaluate their flood resilience as the same process has the potential to be re-used with some adjustments to the chosen 3D city base model. In practise, however, this process might be more difficult because different sources and data qualities will have to be brought together which can turn out to be a difficult and complex process.

6.2.4 Applicability of 3D city flood models for city planners

In regard to Dutch city planners, the listed advantages, the availability of data and the potential scalability of the model play an important role in the applicability of the model. Many city planners might struggle with using the spatial decision tool, especially if they have no programming knowledge at all. In case the small amount of urban planners that do have an affinity to programming, do not have access to a CityGML file of their study area through either their company or municipality, they can make use of the 3D model of 3DBAG and still evaluate the flood resilience of their study area. While setting up the 3DCityDB and enriching the CityGML files of a certain city with additional data is more complex and probably not within the area of expertise of urban planners, once the database for that city is set up and an FME script is written to manipulate and enrich the CityGML files with additional information, urban planners of that city can, with the most rudimentary knowledge of FME, run the script and import the CityGML file into a new schema in the 3DCityDB. Once the 3D data is added to the 3DCityDB, the work process is moved to QGIS, a software that many urban planners have extensive experience with. As to the potential of a spatial planning decision tool to be operated by city planners, the only main difference to evaluating the flood resilience of the current situation is the fact that city planners will have to implement their preliminary designs into the 3D city model which they can do by creating a shapefile of their design in QGIS, running the CityGML script displayed in Appendix G and importing the just created CityGML file into the 3DCityDB. By further developing the tool and developing a dynamic 3D city flood model as the base model, this process has the potential to become more simple. In the future, the tool might be developed to such an extent that the city planner only has to import their new environmental plan and choose a flood scenario to be tested and the model will return a visualization of the chosen flood in the new urban environment as well as the calculated Flood Resilience Scores.

6.3 Points for improvement

Throughout the research, certain decisions were made based on the availability of data and software, the state of 3D city model technology, the scope and time constraint of the research, or the experience of the researcher at the beginning of the research process. In hindsight, there are several points of improvement in regard to the conducted research.

6.3.1 Automating the process

In the previous section, the accessibility for city planners to use the process of developing a 3D city flood model to then make spatial planning decisions in regard to flood resilience is discussed. Currently, the process is a tedious one and includes a lot of manual and case-based adjustments as Chapters 4 and 5 show. The process, therefore, has to be automated by writing multiple scripts that direct all software used in this research and therefore combine the different steps while a front-end GUI (graphical user interface) makes the process more accessible to city planners. Using the GUI, urban planners should only have to choose which area they want to test and 'run' the tool to receive a visualization of the flood and the results from the Flood Resilience Scores. As to testing their preliminary urban design plans, city planners should only have to upload a shapefile of their design, choose the surrounding area they want to take into account and run the tool. Automating the process and making it more accessible to urban planners was not possible during this graduation project. This research, however, can be seen as a proof of concept to see what needs to be done to do so.

While most steps in the process could already be directed by scripts with the right programming knowledge, the information on infrastructure points would still have to be added manually as there is no existing database (except for the one that is only accessible to employees of Dutch municipalities) that has recorded these points and their geolocation (or a primary key to link the infrastructure point to a modelled object with the same key). Now, the infrastructure points are sourced from Google Maps, listed in an Excel document with their corresponding BAG IDs and added to the CityGML files using a 'reader' in FME. If a database and a WFS connection would exist, the process could be automated and the model would be automatically updated with recent data each time the script would be run. Now, however, the process is still a manual one and someone has to update the Excel document including the critical infrastructure points regularly.

6.3.2 Changing the environment of the hydrodynamic simulation model

To test the new spatial design plans for Nieuw Kralingen and to evaluate the potential of a model-based spatial design-decision tool, the built environment in the semantic 3D city model of Rotterdam, as well as the environment in the flood simulation model has to be changed. While changing the building layer of the 3D city model is fairly simple as Section 5.3 shows, changing the base model of the flood simulation model is a different story. To do so, access to a hydrodynamic simulation model is required to change the environment of the flood to fit future environmental plans. The hydrodynamic simulation model '3Di' by a consortium of Stelling Hydraulics, Deltares, TU Delft, and Nelen & Schuurmans, would have been a good choice for this research (3Di Water Management, n.d.) would it have been an open software. Using a simplified 2D model of the study area, the model simulates urban floods based on, among others, future rainfall scenarios and produces inundation maps including the location, intensity, and the duration and development of the flood over time. The 2D model environment is built up of data on the terrain elevation of the study area (DTM), the infiltration and friction rate, as well as obstacles that simulate buildings. Information on the sewage system is added to the model in 1D (De Jonge, 2021). Most importantly though, the underlying 2D model can be adjusted so that the effects of changes in the built environment can be evaluated beforehand. The hydrodynamic simulation model 3Di allows the user to adjust the friction and infiltration rate, as well as the elevation of the area. Buildings can be simulated by placing 'obstacles'. The adjustments to the built environment are done in QGIS as this is the underlying software that 3Di uses. The output data of the flood simulation model is then used as input data for the 3D city model and the impact of the flooding data on the other data layer is evaluated using the Flood Resilience Score. As no access to 3Di was gained, the results of the 3D city flood model in regard to Nieuw Kralingen are based on flood inundation maps that represent a flood scenario using the built environment situation of that time. The Flood Resilience Scores of Nieuw Kralingen are therefore flawed to some extent and urban planners should not make important spatial planning decisions based on these scores until the adjusted flood inundation map is added.

6.3.3 Indicators of the Flood Resilience Score

Some more points of improvement concern the Flood Resilience Score and how it is calculated. The choice of indicators to calculate the Flood Resilience Scores (the amount of directly (and indirectly) affected buildings/households/critical infrastructure points) means that other important aspects of resilience such as the resilience of infrastructure networks are not taken into account. Therefore, no conclusion can be drawn on the resilience of for example the telecommunication-, electricity-, or freshwater network and how they play a role in the (indirect) effect of a flood on a city. At the same time, the process currently does not allow adding infrastructure points (such as electrical boxes, sewage pits, or public transportation stops) to the model that cannot be linked to an already modelled object. If more information on infrastructure networks would be available, an infrastructure point should be added to the 3D city model as a 'GenericCityObject' and not as a generic attribute of an object.

6.3.4 Including critical infrastructure points outside the study area

Not only more different types of infrastructure points would be an improvement to the research, also infrastructure points outside of the study area which would still affect the study area should be included. Now, only critical infrastructure points within the study area are taken into consideration. By not including infrastructure points from outside the study area, the hospitals, police stations and fire brigade which are all located close to the study area but not within, are not taken into account while their impact when flooded is great and would also have an effect on the study area. Including these infrastructure points should furthermore also have an influence on the Flood Resilience Score when it comes to the weighing of the different types of infrastructure points. Now only 4 vital infrastructure points influence the study area which are all supermarkets. It is however unlikely that only 4 supermarkets supply around a total of 99.000 households that are situated in the study area. Because of the small number of vital infrastructure points, several neighbourhoods like Nieuw Kralingen are not impacted by any vital infrastructure points and therefore their Flood Resilience Scores for directly and indirectly affected households and buildings do not vary with the directly affected scores. However, not having any vital infrastructure points within the study area that contribute to the health and well-being of people or avoiding placing vulnerable infrastructure points such as elderly homes in neighbourhoods to score high on the Flood Resilience Score is not the answer (with the exception of dangerous infrastructure points).

6.3.5 Utilize the 'point of entry' of floodwater to determine flooded buildings

Another point of improvement to refine the model is concerning the spatial analysis of determining flooded buildings. Currently, the spatial analysis considers all buildings that intersect the flood inundation map as affected by the flood. However, if the water indeed enters the building, depends on the points of potential entry (assuming that the structure of the building is water-tight) such as windows and doors. It could therefore be said that a building is only affected if the flood is higher than the height of the closest door or window entrance. Taking the actual inundation of the flood and the height of the door opening into account would in theory be another way to assess the impact that a flood has on the city. However, to be able to use this method, one needs to be sure of the accurate scale that the models and inundation maps are using. The most sophisticated inundation maps are generated in raster's of 50cm by 50cm while raster cells of 2m by 2m are more common. So while a map might indicate that an area is flooded, in reality this might not be the case. At the same time, the planimetric and height accuracy of airborne laser scanner data that is used to generate 3D model is likely not to be exact either meaning that the entry of a door or window might be located several decimetres to the side which might mean that a building does or does not flood (Höhle, 2011).

6.4 Recommendations

Based on the research done, several recommendations can be made to future researchers and developers, the overall government, and specific municipalities.

On a more global level, it became clear during the research that a national standard for dividing the Netherlands into raster tiles would be an efficient way to organize and manage geospatial data. Now, different data sources divide and store their data in different raster and raster sizes making the collection of the required data more difficult while often including unnecessary data. A national standard for dividing the Netherlands into raster tiles would therefore allow for greater consistency and interoperability of geospatial data across different organizations and systems. This can facilitate the sharing and integration of geospatial data, enabling more efficient and effective use of the data for a wide range of purposes. As an additional recommendation to the municipality of Rotterdam on the topic of storing and accessing geospatial data, the CityGML files containing 3D information on the buildings and the city furniture of Rotterdam should also be made available for each neighbourhood not only in the form of downloading areas defined by self-drawn bounding boxes.

Another practical standardization would be the regulation of semantic information in the different LoDs for CityGML. Currently, no standardized information on buildings exists such as the requirement to include information on a building's ID, the maximum height of a building, the slope of the roof, a building function, the number of inhabitants living within the building, the total number of stories within the building, and so on. By implementing standard semantic building information, CityGML files might not have to be enriched with additional data, or, by at least standardizing the existence of a building ID, buildings can be more easily enriched with additional data from another data source.

During the development of the semantic 3D city model, it became clear that there are several geometric and 'unique ID' mistakes within the official data obtained from Rotterdam3D which made developing the semantic 3D city model a long and tedious process. Among others, buildings were categorized as building parts, not buildings, the downloaded tree files were not valid so the structure of the files had to be changed, some of the bicycle racks in the city furniture files were greatly oversized, and XLink reference errors (where an ID that should be unique, is not) in the solitary vegetation files and the city furniture files led to difficulties when it came to importing several CityGML files. By eliminating these errors, the municipality of Rotterdam would make the process of evaluating the flood resilience of a study area more accessible to urban planners which increases the potential of the model being utilized for urban planning decisions in the future.

While the semantic 3D city flood model focused on evaluating the flood resilience of cities, the model can also be used for other purposes. First responders for example can use the model to know which vulnerable areas or buildings (such as elderly homes) should be prioritized during an evacuation or which dangerous infrastructure points need intervention during a flood. Additionally, data output from other climate-related events such as droughts or storms can be inserted into the semantic 3D model to gain insight into a city's overall climate resilience and act accordingly.

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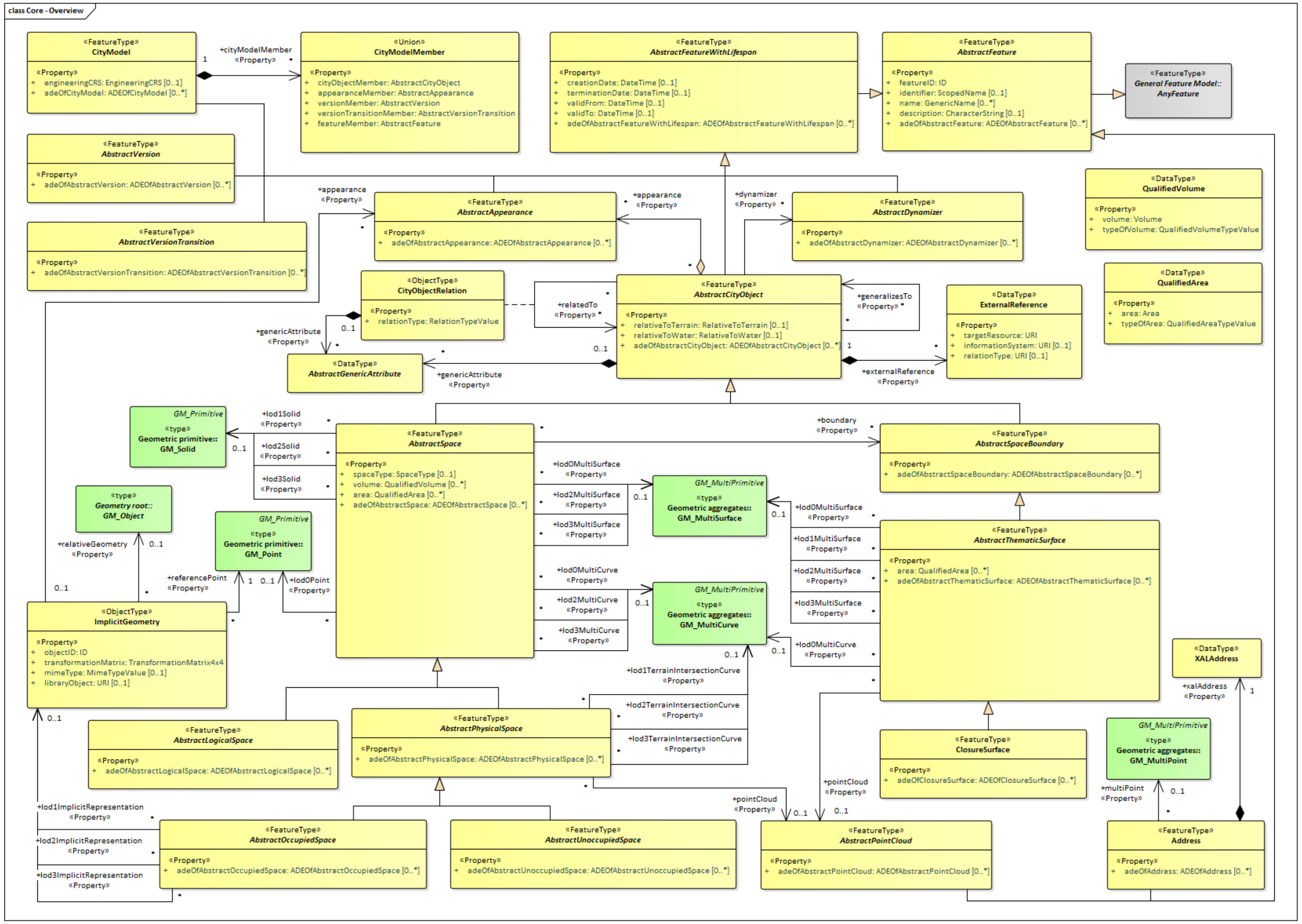
Appendices

Appendix A - Overview of the UML model for the core of CityGML



Appendix B - Comparing base models

This research builds upon an already existing 3D base model of Rotterdam to develop it further and utilize it for city planners to evaluate the impact of heavy rainfalls on the current built environment as well as to evaluate the impact using an adjusted built environment. There are two publicly and freely accessible datasets that model Rotterdam; 3D BAG and Rotterdam 3D. A comparison is needed to find out which of the two datasets is best to use for this research.

The 3D BAG data is provided in CityJSON, not CityGML. To compare the two, the data is converted from a CityJSON format to a CityGML file using the converter 'citygml-tools' developed by the TU Delft. The two files of the study area in Rotterdam are first compared visually to determine their refined LoD specification and to see which of the models is closest to reality. Then, the completeness of the models is compared by investigating the data sources that the models use and the most recent time the 3D models were synchronized with their data sources, followed by determining the area that can be downloaded. The content of the two data models is compared including potential additional object content as well as the presence of generic building attributes. Finally, the applicability of the two models in different research areas is explored.

Visual comparison

As explained in Section 2.3.1.6, the Level of Detail (LoD) of a 3D model determines the amount and degree of building detail that is represented in the 3D model. 3D BAG allows the users to download CityGML files in either LoD 1.2, 1.3, or 2.2, using the refined LoD specification by Biljecki et al (2016). While Rotterdam 3D also allows users to download either in LoD 1 or LoD 2, the refined LoD specifications are not used. To find out which LoD 2 classification Rotterdam 3D uses, an excerpt from the 3D model is compared to the refined LoD specification table by Biljecki et al (2016).

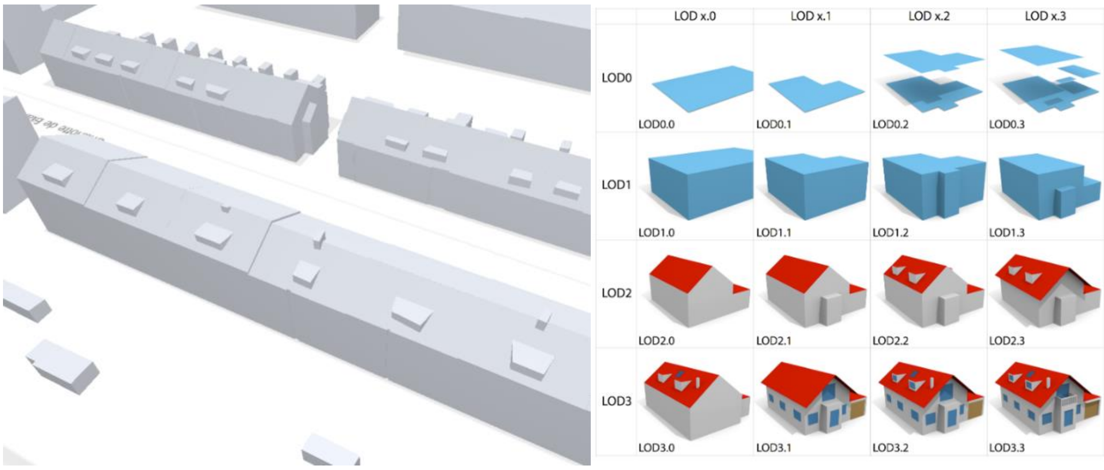


Figure 107. Visual comparison of Rotterdam 3D (Gemeente Rotterdam, n.d.-a) in LoD 2 to the refined LoD specification by Biljecki et al (2016).

The visual comparison in Figure 107 clearly shows that the 3D model of Rotterdam can be classified as LoD 2.2; dormers are included in the 3D model while roof overhangs are not.

Even though both models use LoD 2.2, some discrepancies between the two models and the reality might still exist. Therefore, two existing buildings in Kralingen Oost each with two addresses are compared to their satellite image in Google Maps. Rozenburglaan 11, 13, 15, and 17 are depicted and compared in Figure 108.

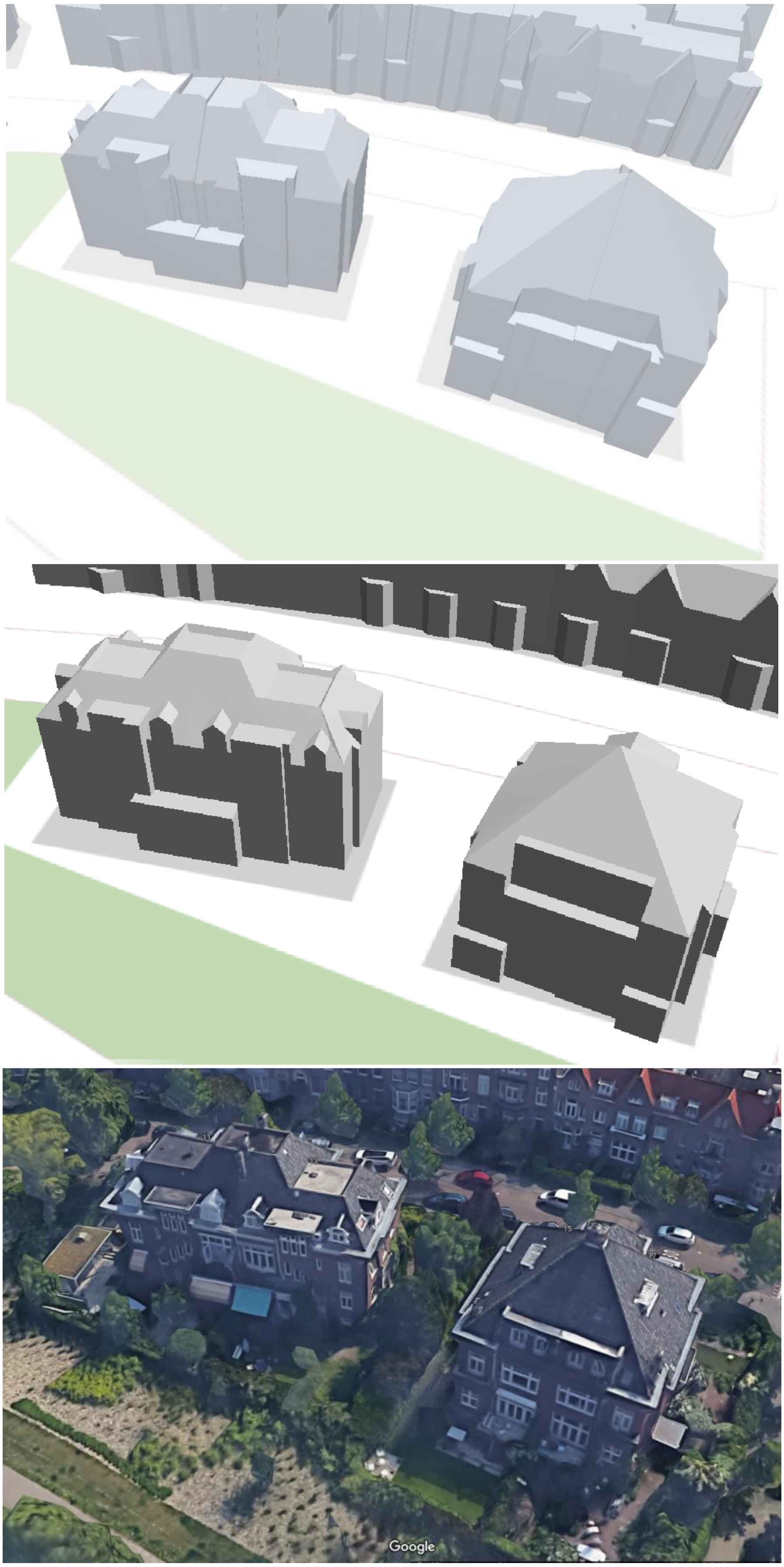


Figure 108. LoD 2.2 comparison between 3D BAG (top) and Rotterdam 3D (middle) and Google Maps (n.d.).

The visual comparison shows that while 3D BAG uses LoD 2.2, the dormers on the left building are not included for this example while Rotterdam 3D does include them. Checking the satellite image from Google Maps shows that the left building indeed has several dormers. At the same time, in reality, the right building has a dormer on the left and the right side of the building, but these dormers are non-existent in either of the 3D models. The same is true for the shed in the garden of the left building and the house extension on the right side of the right building. Overall, however, the shape of the two buildings in 3D BAG and Rotterdam 3D are fairly similar.

While for a flood simulation these slight differences in shape might be more important due to changes in rainwater run-off, the flood simulation that is used in this research uses its own model. Therefore, the slight differences in shape in the 3D base models do not affect the results of this research and can therefore be neglected. What is important, however, is the completeness of the 3D model.

Data sources & most recent synchronization

To answer the question, which of the 3D base models is more 'complete', one has to investigate the data source of the 3D model as well as the most recent time the model was synchronized with its data sources.

According to TUDelft3D (n.d.), 3D BAG is built upon source data from BAG (Register of Building and Addresses), AHN3 (National Height Model of the Netherlands), BGT (Large Scale Topographic Map), and TOP10NL (from the Topographic Register). The 3D model is *"regularly updated"* with the BAG dataset (TUDelft3D, n.d.), however, a timestamp or indication of what 'regular' means, is not given. As of June 2022, 'Blok 59', 'SIXTY5', 'Haasje Over', and the 'Trudo Tower' – all buildings located on Strijp-S in Eindhoven – have not yet been added to the 3D BAG model of the Netherlands. Their dates of completion – Blok 59 in 2018 (Adviesbureau Tielemans, n.d.-a), SIXTY5 in mid-2020 (Adviesbureau Tielemans, n.d.-b), Haasje Over in 2021 (Adviesbureau Tielemans, n.d.-c), and the Trudo Tower in 2021 (Adviesbureau Tielemans, n.d.-d) - indicate that the 3D BAG model has not been updated since 2018 (or the municipality of Eindhoven has not added these buildings to the BAG register). The data of the AHN3 that 3D BAG uses was collected between 2014 and 2019. Because the building stock only changes slowly over time, the TUDelft3D (n.d.) estimates that 95% of the measured building heights in the 3D model are still valid. In general, the TOP10NL consists of national data on buildings, as well as on terrain which can be used for visualization purposes. 3D BAG only uses the TOP10NL database to identify buildings such as greenhouses and warehouses.

Meanwhile, Rotterdam 3D also uses source data from BAG and BGT but additionally makes use of source data from BOR ('Beheer Openbare Ruimte' = Public Space Management) and LVZK ('Leidingen Verzamelkaart' = City map of pipes and cables) (Gemeente Rotterdam, n.d.-c). The latter one, however, cannot be downloaded by the public. Adding the LVZK to the 3D model also does not have added value to this research as the CityGML file only represents the built environment above ground, not below and the impact of a flood on the underground infrastructure is unclear. Compared to the 3D BAG model, Rotterdam 3D does not make use of the TOP10NL database which 3D BAG does to identify, among others, greenhouses and warehouses. However, looking at the Wallhaven, an industrial neighborhood in Rotterdam with many warehouses, shows that Rotterdam 3D does include these warehouses in its model even though TOP10NL is not utilized.

According to the municipality of Rotterdam, there are national agreements with the government that municipalities have to keep the national BAG and BGT database up-to-date, as well as internal agreements concerning the BOR. In the case of Rotterdam, the municipality updates the BAG and BGT databases daily.

This however does not mean that the 3D city model is also synchronized with the BAG and BGT daily, this synchronization instead happens every year or every other year according to the municipality of Rotterdam. Objects in the public space (BOR) and cable- and pipe networks (LVZK) meanwhile are synchronized with the 3D model every month and the terrain model is updated every second year. While the municipality of Rotterdam is more transparent about how often their 3D model is updated compared to the TUDelft3D, there are also no indications of when the most recent synchronizations took place.

To conclude, it seems that of June 2022 (the moment the study area was downloaded), Rotterdam 3D was more recently synchronized with its source databases and should therefore be more 'complete'.

Downloadable area

The area that can be downloaded in batches also varies between the two 3D models. 3D BAG divides Rotterdam (and the rest of the Netherlands) into quadrant tiles. The size of the area that a tile covers depends on the amount of data within the tile; the tiles that cover areas with a high density of buildings and objects are small in geographic size while tiles in rural areas are bigger. The size of the quadrants multiplies by 4 to be able to cover the country raster-like.

In the meantime, 3D Rotterdam divides the city and its corresponding model by neighbourhood but also allows the user to download a polygon area of their choosing.

The different area sizes influence the exact location of the study area. Figure 109 shows the study area that is used when 3D BAG is chosen while Figure 110 depicts the chosen neighbourhoods that surround Nieuw Kralingen.

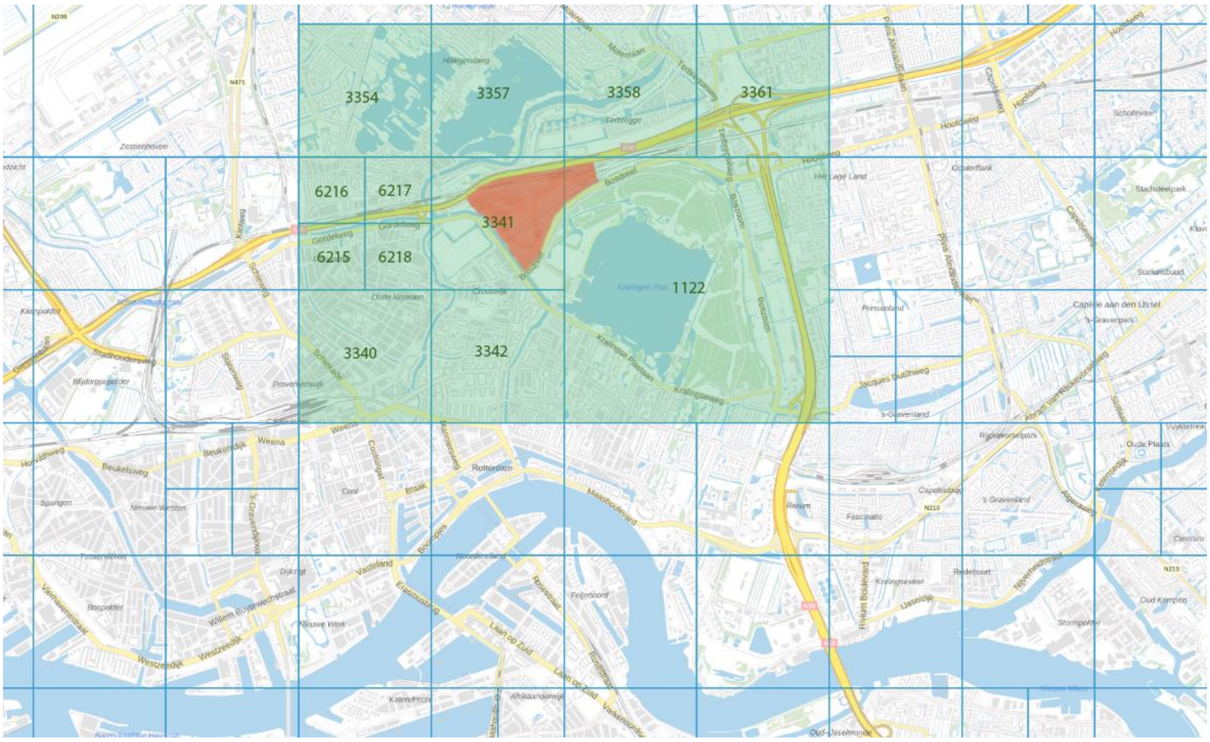


Figure 109. Chosen study area in 3D BAG.

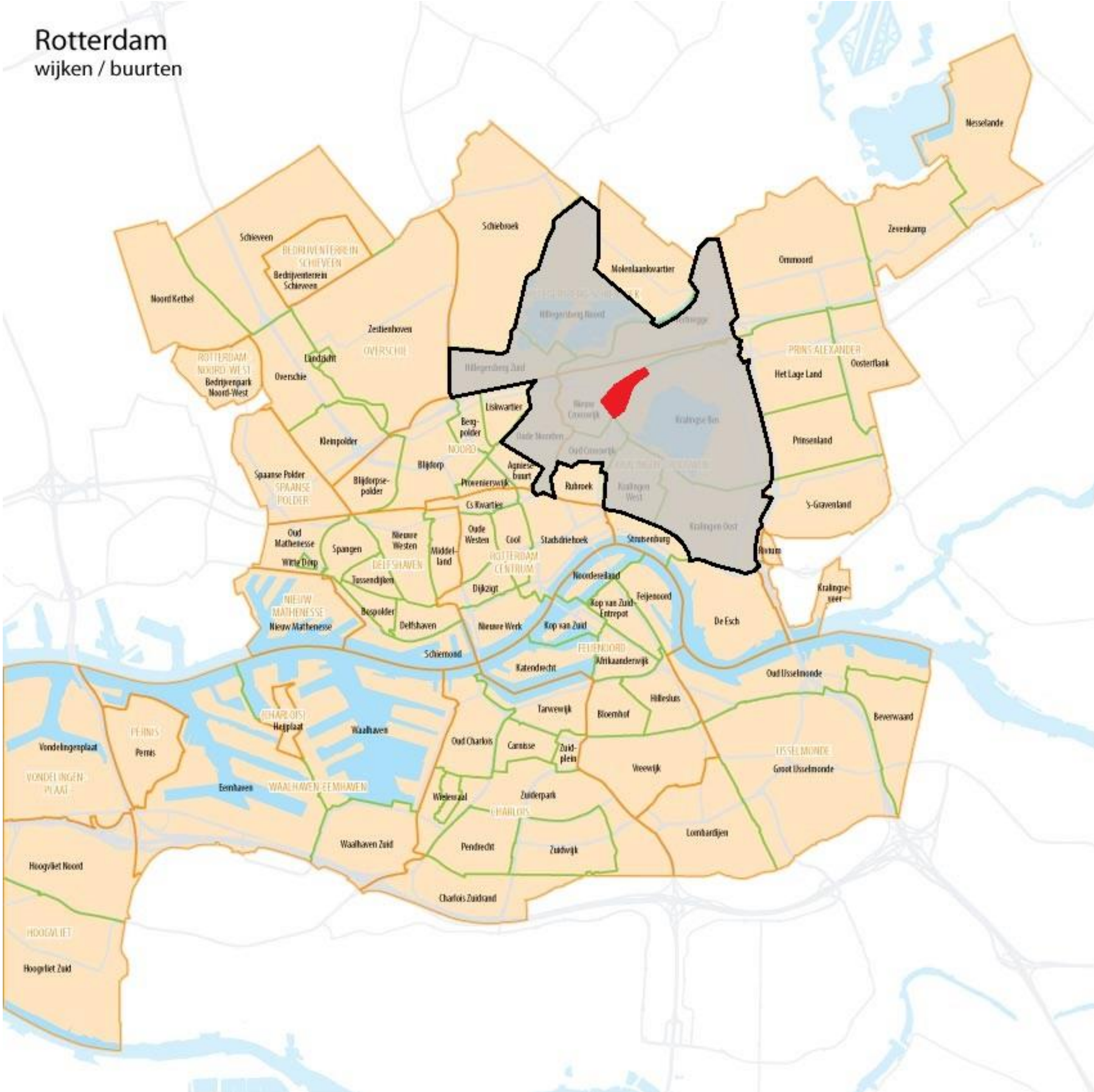


Figure 110. The chosen study area for Rotterdam 3D.

Comparing Figure 109 and 110 shows that the chosen study area for Rotterdam 3D is much greater than that of 3D BAG because most of the neighbourhoods that were chosen because they fall within the rough estimated study area in Figure 39 (Section 3.2), also reach beyond this area. Meanwhile, a flood is dependent on the geographical characteristics of an area and does not stop at the border of a neighbourhood. Making use of a greater study area – as is the case for this research - might reveal starkly contrasting flood resilience scores in different parts of the study area that might not be discovered using a smaller study area. Also, while this research is a proof of concept, using a greater study area can indicate if a scale-up of the model is possible.

Content comparison

The content of the CityGML files plays one of the most important roles in choosing a 3D base model. Here, content is referred to as additional information and objects in the built environment as well as additional information/(generic) attributes associated with the buildings.

While 3D BAG only allows its users to download buildings, Rotterdam 3D also provides additional downloadable CityGML files including bridges, city furniture, and solitary vegetation objects (trees). Because Rotterdam is encompassed by waterways, bridges are important infrastructure objects and their closure can have a disruptive effect on the city's infrastructure. These additional files however are downloaded separately from the building layer of the Rotterdam 3D model and can therefore also be used in combination with the 3D BAG model.

What makes the 3D city models semantic is the additional (building) information that TUDelft3D and the municipality add to their CityGML files, specifically the generic attributes of the buildings. Finding out what kind of information is added to each of the models will support the decision; which of the two models is more suitable for this research? To 'view' the generic attributes in the data files, the FZK Viewer is used (more information on the FZK viewer can be found in Section 3.3.2). The same building was chosen in both models to be able to compare the data. Figure 111 shows a comparison of the properties embedded in the CityGML files using a tower in Oud-Crooswijk on the Boezemsingel 314-480 with the BAG-ID 0599100000611391.

At first glance, 3D BAG includes more building properties than Rotterdam 3D. Attributes such as the type of the roof (dak_type), the roof part ID (dd_id), a geometry ID (gid), information on whether the building has a green house or warehouse function (kas_warenhuis), information on the acquisition of the point cloud before or after the construction of the building (pw_actueel), or the source of the point cloud (pw_bron) are included. Other attributes have different tags but the same value; 'status' (3D BAG) and 'statusOmschr' (Rotterdam 3D) both inform the user of the current phase of the building's life-cycle, 'oorspronkelijkbouwjaar' (3D BAG) and 'bldg:yearOfConstruction' (Rotterdam 3D) both refer to the building construction year, while 'identificatie' (3D BAG) and 'gml:id'/'gebouwnummer' (3D Rotterdam) state the BAG ID of the building. Both CityGML files also include the measured height of the building. However, the value of this attribute deviates. In 3D BAG the measured building (h_dak_max) is 79.272 meters high, while the same building in Rotterdam 3D (bldg.:measuredHeight) is 78.01 meters high.

While Rotterdam 3D contains fewer attributes, it does record the addresses assigned to the building as well as the number of building layers (aantalBouwlagen). Especially the former is an important generic attribute that has to be included in the 3D model.

Overall, information is displayed clearer in Rotterdam 3D and seems to be more relevant at first glance. The additional information provided by TUDelft3D however is important for studies concerning for example calculating the solar potential of buildings but not important for this study in particular.

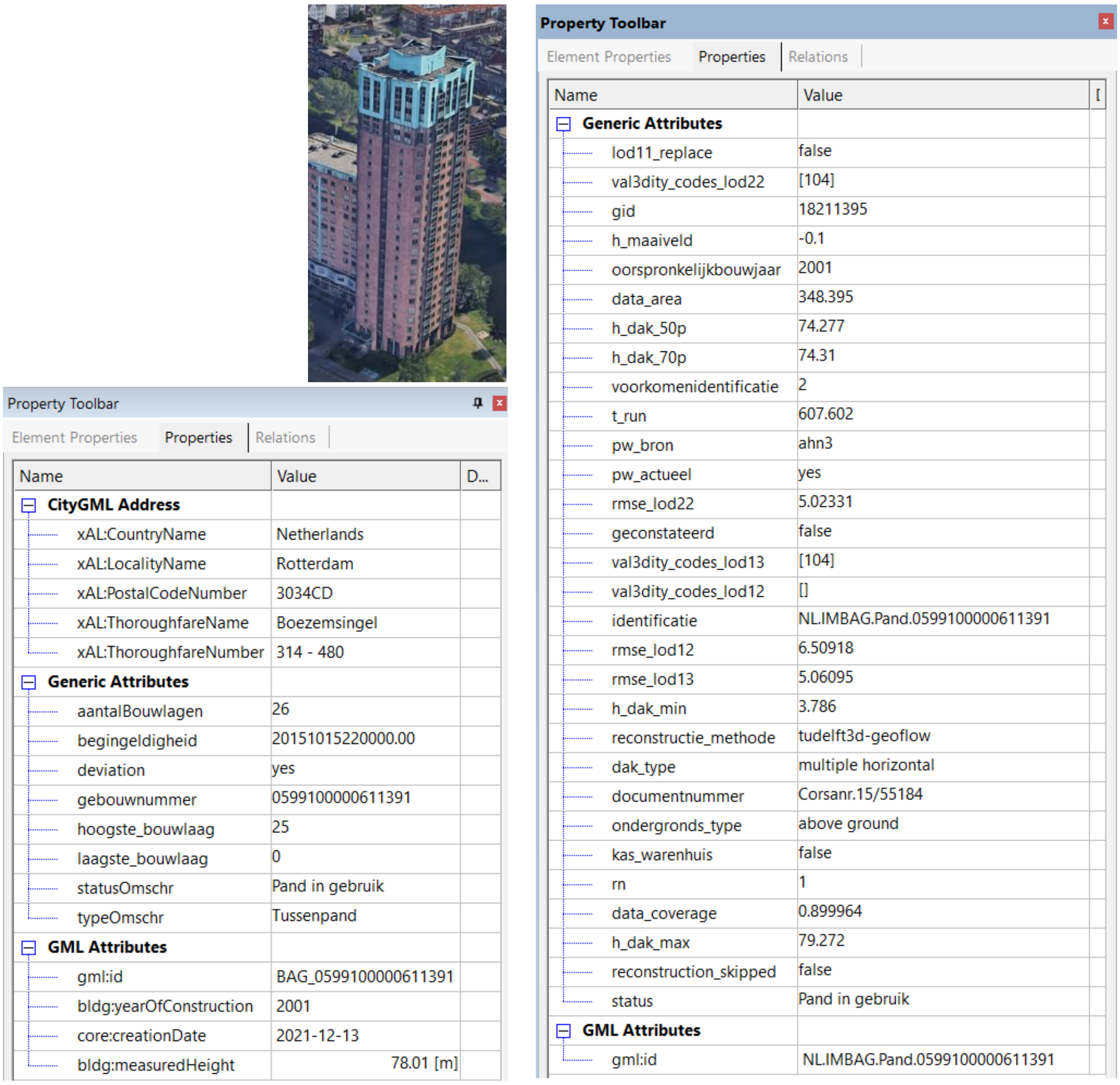


Figure 111. Comparison of building properties between Rotterdam 3D (bottom left) and 3D BAG (right) using Boezemsingel 314-480, Rotterdam (top left).

Applicability

While this research is meant as a proof of concept and only focuses on a certain area in Rotterdam, in the end, the method developed in this research and the spatial planning support tool should be applicable to any city in the Netherlands or even the whole country. Because 3D BAG covers all of the Netherlands while Rotterdam 3D only covers Rotterdam, choosing the 3D BAG as a base model seems the smarter choice for future research as the FME script will likely vary based on the chosen 3D base model. However, the CityGML files are fairly similar and when automizing the process of this research in the future so that the spatial planning support tool becomes more accessible to city planners, only the FME script has to be slightly adapted.

For municipalities – who are the target audience - it is also easier to add generic attributes to their 3D model instead of waiting for the 3D BAG model to be adjusted for all of the Netherlands. Being independent of other parties and being able to add all the required building attributes to the 3D city model would also mean that the municipality would not require the FME software to add attributes to the CityGML file later on.

Conclusion

Based on the insights gained throughout this comparison, Rotterdam 3D was chosen as the 3D base model for this research. A short overview of the comparison of 3D BAG and Rotterdam 3D is given in Table 3.

Table 3. Overall comparison of 3D BAG and Rotterdam 3D.

	3D BAG	Rotterdam 3D
Visual comparison	neglectable	neglectable
Last synchronization	<= 2018	Unclear (margin set to 2 years)
Data sources	similar	similar
Downloadable by…	tile	Neighborhood
Additional content	none	Bridges & solitary vegetation objects
General attributes	Many additional attributes not important for this study	Includes addresses
Application area	The Netherlands	Rotterdam

Appendix C - Amount of buildings and bounding boxes per neighbourhood

Amount of buildings per neighbourhood

Neighbourhood	Amount of buildings	Amount of addresses	Amount of city objects
Hillegersberg Noord	4.106	2.859	51.460
Hillegersberg Zuid	4.383	3.182	57.596
Kralingen Oost	3.781	2.467	57.175
Kralingen West	3.841	2.785	43.371
Kralingse Bos	426	387	5.124
Nieuw Crooswijk	1.001	697	11.476
Oud Crooswijk	1.654	938	19.753
Oude Noorden	4.888	3.467	56.773
Struisenburg	769	438	11.564
Terbregge	2.631	2.122	28.383
Total amount of buildings per neighbourhood	27.480	19.342	342.675

Bounding boxes of neighbourhoods

	Bounding box			
Neighbourhood	x_{min}	x_{max}	y_{min}	y_{max}
Hillegersberg Noord	92352,82	94568,3	440102,42	442627,657
Hillegersberg Zuid	91268,39	93267,611	439427,853	440486,61
Kralingen Oost	94624,15	96504,94	436563,464000011	438335,08
Kralingen West	93796,7600000001	94831,96	437319,11	438686,33
Kralingse Bos	94059,11	96545,241	437915,32	440325,35
Nieuw Crooswijk	93063,479	94665,6420000076	438769,14	440085,670000005
Oud Crooswijk	93053,06	94108,0700000001	438222,780999999	438988,95
Oude Noorden	92119,95	93269,45	437822,39	439730,26
Struisenburg	93821,445	95176	436764,247000003	437536,7
Terbregge	93036,79	95942,02	439799,07	441666,64
Overall study area	91268,39	96545,241	436563,464000011	442627,657

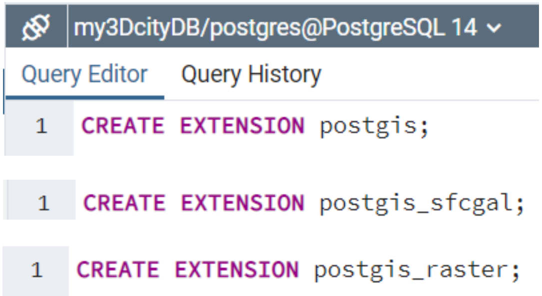
Bounding boxes of City Furniture Tiles:

	Bounding box			
Tiles	x_{min}	x_{max}	y_{min}	y_{max}
Tile 1	91268,39	93027	442121	442627,657
Tile 2	93027	94786	442121	442627,657
Tile 3	94786	96545,241	442121	442627,657
Tile 4	91268,39	93027	441100	442121
Tile 5	93027	94786	441100	442121
Tile 6	94786	96545,241	441100	442121
Tile 7	91268,39	93027	440100	441100
Tile 8	93027	94786	440100	441100
Tile 9	94786	96545,241	440100	441100
Tile 10	91268,39	93027	439216	440100
Tile 11	93027	94786	439216	440100
Tile 12	94786	96545,241	439216	440100
Tile 13	91268,39	93027	438332	439216
Tile 14	93027	94786	438332	439216
Tile 15	94786	96545,241	438332	439216
Tile 16	91268,39	93027	437448	438332
Tile 17	93027	94786	437448	438332
Tile 18	94786	96545,241	437448	438332
Tile 19	91268,39	93027	436563,464000011	437448
Tile 20	93027	94786	436563,464000011	437448
Tile 21	94786	96545,241	436563,464000011	437448

Appendix D - Setting up the 3DCityDB

To be able to store the 3D city data that was obtained and checked in the former steps, the SQL database 3DCityDB first has to be set up. The 3DCityDB is built upon an existing installation of either PostgreSQL or Oracle. For this research, PostgreSQL was chosen and set up. Another system requirement that is needed before being able to store 3D city data, is Java, which is required to run the importer/exporter tool of the 3DCityDB. The Java distributer Oracle Java 17 LTS (long-term support) was chosen for this research over 'Eclipse Temurin', 'Amazon Coretto', and 'OpenJDK' as it provides a no-fee, free-to-use license.

After running the 3DCityDB Importer/Exporter installer, the 3DCityDB schema is set up. A database is created in PostgreSQL labelled 'my3DcityDB' and the owner is set to 'postgre'. A PostGIS extension is created in the new database to enable all spatial functions and data types (see Figure 112). To allow 3D operations such as extrusions or volume calculations, the extension 'postgis_sfcgal' is added (see Figure 113) followed by the extension 'postgis_raster' as 3DCityDB requires the raster functionality (see Figure 114). (Note: The last extension is only necessary for PostGIS versions equal to or higher than version 3 as the raster functionality was moved to a separate extension)



Figures 112 to 114. Command lines to set up the database in PostgreSQL.

By editing the CONNECTION_DETAILS script in the installation directory of the Importer/Exporter, the database credentials are defined and a new database can be created. Starting the shell script CREATE_DB.bat embedded in the installation directory of the Importer/Exporter prompts the 3DCityDB Command Prompt window to open, set up, and connect the 3DCityDB to the PostgreSQL database. During this process, the coordination reference system that the 3D city model uses has to be specified. In the Netherlands, the Spatial Reference Identifier code (SRID) - also called EPSG - that is used for the geometry columns of the database, is 28992, while the EPSG code of the height system is 5709. Combined, these codes form the following GML compliant uniform resource name (URN) encoding of the CRS: 'urn:ogc:def:crs,crs:EPSG::28992,crs:EPSG::5709'. As a last step, to connect the 3DCityDB to the PostgreSQL database, the password for user 'postgre' (the researcher of this thesis) is entered.

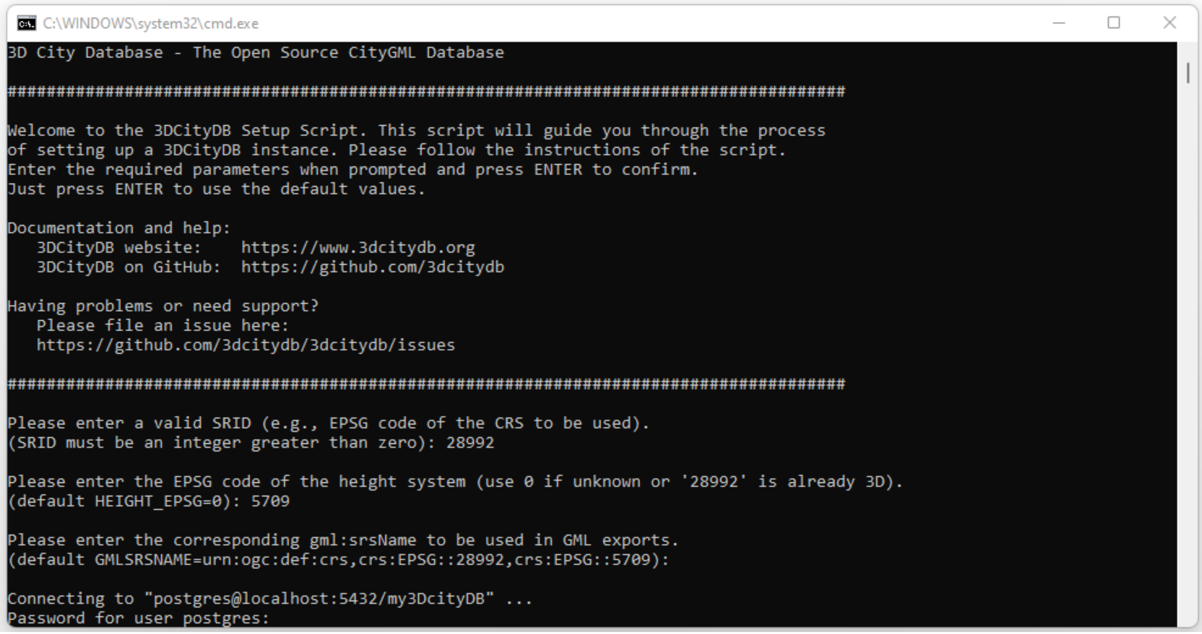


Figure 115. Setting up and connecting the 3DCityDB to the PostgreSQL database.

If the setup was successful, two schemas – 'citydb' and 'citydb_pkg' - are automatically added to the PostgreSQL database. The 'citydb' schema is a default schema that can store the 3D city database while the 'citydb_pkg' contains scripts that create database objects and store procedures used by the Importer/Exporter tool. The advantage of using multiple schemas instead of multiple databases for different projects/data within one project is that tables from different schemas can be joined while queries across databases are much more difficult if not impossible in PostgreSQL. Additional schemas are therefore created to store data separately and to be able to evaluate the neighbourhoods separately. These schemas are created by running the CREATE_SCHEMA.bat script instead of creating the schemas directly in PostgreSQL which will not load the table layout of the 3DCityDB into the schema. When executing the script, the name of the schema has to contain only lower cases.

The last step in setting up the 3DCityDB is connecting the Importer/Exporter to the PostgreSQL by setting the correct database and schema in the database tab of the Importer/Exporter to 'my3DCityDB' and 'citydb', respectively (see Figure 116). Now the 3DCityDB is set up.

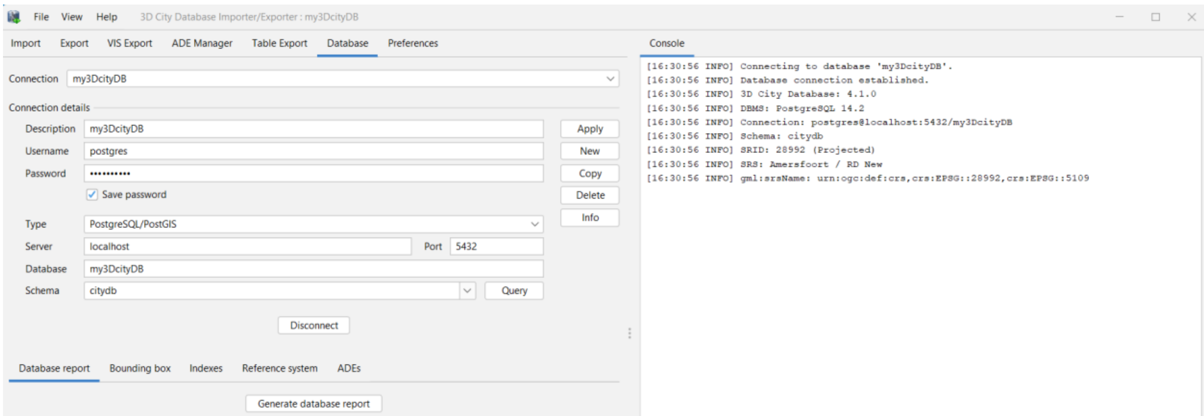
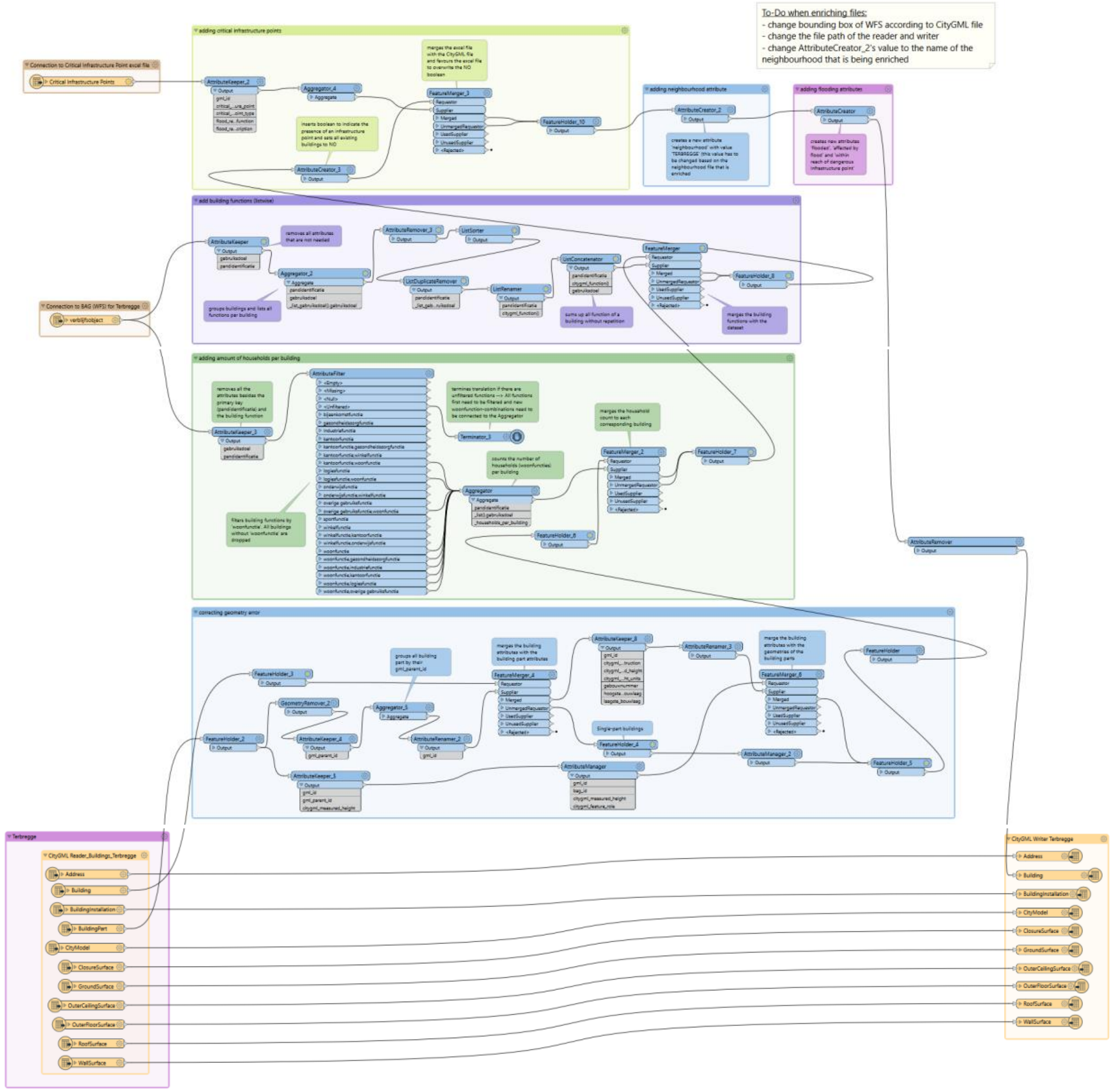
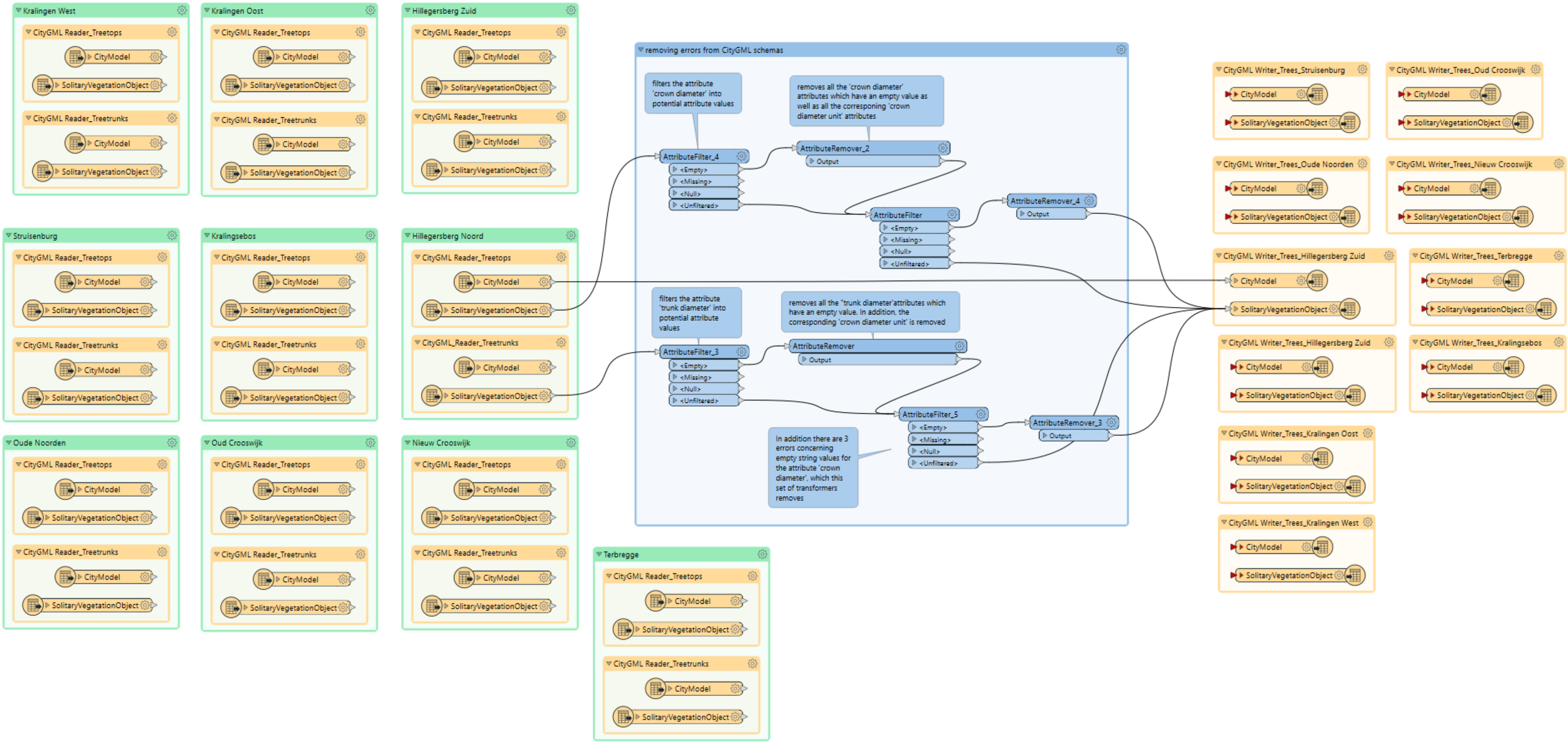


Figure 116. Connecting the Importer/Exporter to the 'my3DcityDB' in PostgresSQL.

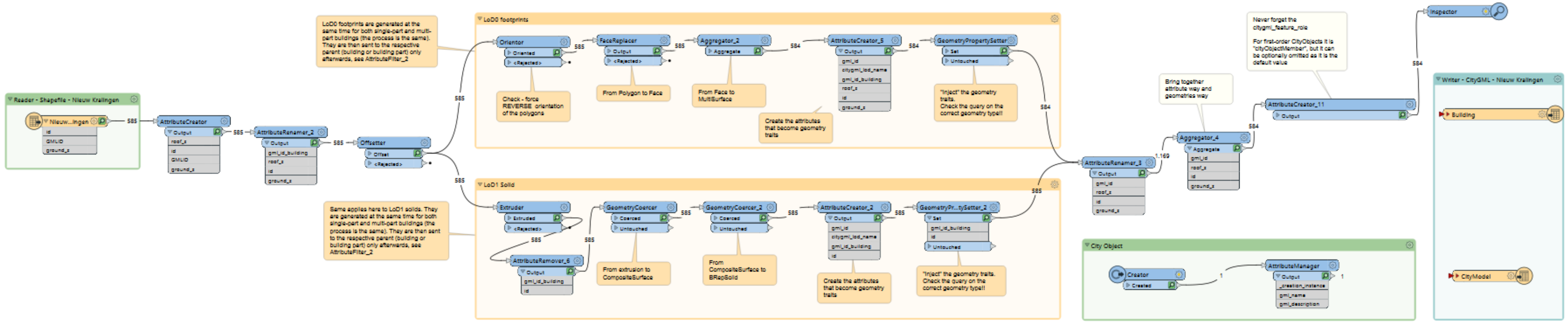
Appendix E - FME workbench for building files



Appendix F - FME workbench for tree files



Appendix G - FME workbench to change Nieuw Kralingen shapefile to CityGML



Appendix H - Overview of numbers and Flood Resilience Scores

OVERVIEW

Scenario	Households			Buildings			Infrastructure points					
	Total amount of households in the study area	Total amount of households directly affected by the flood	Total amount of households directly and indirectly affected by the flood	Total amount of buildings in the study area	Total amount of buildings directly affected by the flood	Total amount of buildings directly and indirectly affected by the flood	Total amount of vital infrastructure points	Total amount of vulnerable infrastructure points	Total amount of dangerous infrastructure points	Total number of flooded vital infrastructure points	Total number of flooded vulnerable infrastructure points	Total number of flooded dangerous infrastructure points
1 - total study area (70mm/2h)	98811	47179	57000	23883	11657	13678	4	53	0	4	27	0
2 - total study area (140mm/2h)	98811	56505	63540	23883	13679	15089	4	53	0	4	30	0
3 - Hillegersberg Noord	14587	4042	4042	3595	1210	1210	0	9	0	0	3	0
4 - Hillegersberg Zuid	6113	2836	2836	3810	1945	1945	0	1	0	0	1	0
5 - Kralingen Oost	7037	3369	3369	3232	1344	1344	0	17	0	0	10	0
6 - Kralingen West	18455	9328	14010	3363	1960	2969	2	12	0	2	10	0
7 - Kralingse Bos	28	7	7	416	100	100	0	5	0	0	2	0
8 - Nieuw Crooswijk	7653	4680	4680	902	506	506	0	3	0	0	1	0
9 - Oud Crooswijk	11018	5040	5040	1347	635	635	0	0	0	0	0	0
10 - Oude Noorden	18091	11170	14290	4200	2690	3557	2	3	0	2	3	0
11 - Struisenburg	14165	6063	6063	635	329	329	0	3	0	0	2	0
12 - Terbregge	1664	644	644	2383	938	938	0	0	0	0	0	0
13 - Nieuw Kralingen (70mm/2h)	800	343	343	584	250	250	0	0	0	0	0	0
14 - Nieuw Kralingen (140mm/2h)	800	456	456	584	333	333	0	0	0	0	0	0

FLOOD RESILIENCE SCORE

Scenarios	Flooded households	Directly and indirectly affected households	Flooded buildings	Directly and indirectly affected buildings	Vital Infrastructure Points	Vulnerable Infrastructure points	Dangerous Infrastructure points
1 - total study area (70mm/2h)	52,3%	42,3%	51,2%	42,7%	0,0%	49,1%	100,0%
2 - total study area (140mm/2h)	42,8%	35,7%	42,7%	36,8%	0,0%	43,4%	100,0%
3 - Hillegersberg Noord	72,3%	72,3%	66,3%	66,3%	100,0%	66,7%	100,0%
4 - Hillegersberg Zuid	53,6%	53,6%	49,0%	49,0%	100,0%	0,0%	100,0%
5 - Kralingen Oost	52,1%	52,1%	58,4%	58,4%	100,0%	41,2%	100,0%
6 - Kralingen West	49,5%	24,1%	41,7%	11,7%	0,0%	16,7%	100,0%
7 - Kralingse Bos	75,0%	75,0%	76,0%	76,0%	100,0%	60,0%	100,0%
8 - Nieuw Crooswijk	38,8%	38,8%	43,9%	43,9%	100,0%	66,7%	100,0%
9 - Oud Crooswijk	54,3%	54,3%	52,9%	52,9%	100,0%	100,0%	100,0%
10 - Oude Noorden	38,3%	21,0%	36,0%	15,3%	0,0%	0,0%	100,0%
11 - Struisenburg	57,2%	57,2%	48,2%	48,2%	100,0%	33,3%	100,0%
12 - Terbregge	61,3%	61,3%	60,6%	60,6%	100,0%	100,0%	100,0%
13 - Nieuw Kralingen (70mm/2h)	57,2%	57,2%	57,2%	57,2%	100,0%	100,0%	100,0%
14 - Nieuw Kralingen (140mm/2h)	43,0%	43,0%	43,0%	43,0%	100,0%	100,0%	100,0%