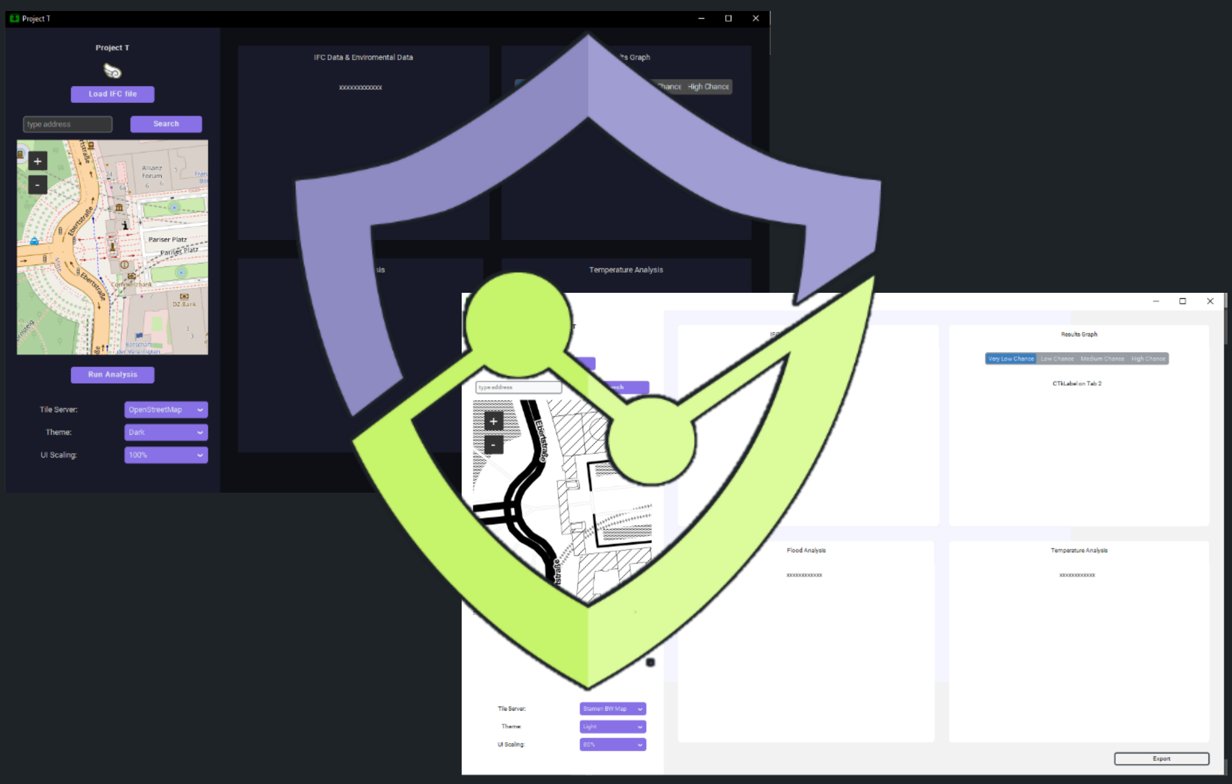
DIGITAL DESIGN TOOL FOR CLIMATE CHANGE RESILIENT BUILDINGS

Designing an open-source Python tool to assess the climate resilience of structural IFC models regarding Climate Change in the Netherlands.



MSc Building Technology Graduation Thesis – Eda Akaltun 5419123

ACKNOWLEDGEMENTS

I want to express my sincere gratitude to all those who have been with me throughout this fulfilling journey of writing my thesis.

First and foremost, I extend my sincere appreciation to my supervisors, Simona Bianchi and Azarakhsh Rafiee. Their exceptional guidance, invaluable expertise, and belief in my abilities have shaped this thesis. Their insightful feedback and encouragement have pushed me to be able to finish my thesis.

I would also like to thank my fellow students, who have been a constant source of inspiration and intellectual stimulation. Engaging in thought-provoking discussions, exchanging ideas, and sparring with them on their theses and mine have enriched my perspective and contributed significantly to my motivation and self-reflection.

Apart from that, no words can express my appreciation to my dear family and friends. Their unwavering support, understanding, and belief in my abilities have been the thing that sustained me throughout this challenging journey. I am profoundly grateful for their presence and cherish them greatly.

Lastly, I am humbled and grateful for the contributions of all who have contributed to completing this thesis, whether big or small. Your support, guidance, and unwavering belief in my abilities have made this journey all the more meaningful and rewarding. Thank you, from the depths of my heart, for being there for me every step of the way.

GLOSSARY

IPCC 2 Report: The IPCC (Intergovernmental Panel on Climate Change) Second Assessment Report assesses the state of knowledge on climate change, including its causes, potential impacts, and possible response strategies. It was published in 1995 and was the second in five assessment reports.

IPCC Scenarios: The IPCC scenarios are a set of possible future projections of greenhouse gas emissions, climate change impacts, and response strategies developed by the IPCC. They are used to explore and analyze different possible futures based on predictions regarding the future.

KNMI: The KNMI (Royal Netherlands Meteorological Institute) is the Dutch national meteorological institute. It is responsible for research on climate and weather-related topics.

KNMI Klimaatsignaal: KNMI Klimaatsignaal is an initiative of the KNMI to communicate climate change and its impacts to the general public regarding the influences specifically on the Netherlands. It provides information on observed changes in climate-related events, such as heatwaves, precipitation, and sea level rise, as well as predicted changes concerning the climate.

KNMI Klimaatscenarios: KNMI Klimaatscenarios are projections of future climate change for the Netherlands and surrounding regions. This is on a range of possible future greenhouse gas emissions. Klimaatscenarios is a more in-depth and detailed Klimaatsignaal.

IFC: IFC, or Industry Foundation Classes, is an open and neutral file format used in the architectural, engineering, and construction (AEC) industry to exchange digital data across various software programs.

The Arrhenius equation:The Arrhenius equation expresses the temperature dependency of reaction rates in chemical reactions and other processes mathematically. The equation has the name of Svante Arrhenius, a Swedish scientist who initially suggested it in 1889.

Klimaateffectatlas: The Klimaateffectatlas (Climate Impact Atlas) is an online tool developed by the Dutch government to provide information and maps about the potential impacts of climate change in the Netherlands. The website provides maps and an API regarding flooding, waterlogging, drought and heat. The atlas uses Klimaatscenarios from KNMI.

Open-Source: Open-source signifies software, hardware, or anything else whose source code and design are available to the public and free for anyone to use, alter, and distribute.

API: Application Programming Interface is referred to as API. It is a collection of rules, procedures, and resources that enables interaction and communication between various software programs.

GUI: Stands for Graphical User Interface. The term refers to a visual interface allowing users to interact with computers through graphical elements.

UI: Stands for User Interface. The UI comprises the design, layout, and interface functionalities. Focuses on user efficiency and effectivity.

UX: Stands for User Experience. The UX consists of the experience that a user has when interacting with the interface. Focuses on user understanding and behavior.

Tkinter: Python library that provides functions for creating GUIs, it is made relatively simple because of GUI components that allow developers to work with buttons, text boxes, menus and other elements. Tkinter can be ran cross-platform on windows, macOS and Linux.

Front-end: Front-end refers to the portion of an application where users directly interact with. Basically, the front face of the code/script.

Back-end: Back-end refers to the processing, managing and performing side of the code/script. Manages the communication between front-end.

Resilience: Ability to withstand and recover from events. In this thesis the events are climate change related.

SUMMARY

Due to global warming, the Netherlands is experiencing a variety of climatic changes, including temperature rise, increased solar radiation and condensation, low pressure, high humidity, wildfires, drought, subsidence, changes in groundwater levels, an increased risk of flooding, and downbursts, thunder, wind gusts, and hail. Building materials, including steel, concrete, and timber are affected directly or indirectly by these climatic events.

When it comes to resilience, increasing moisture, temperature, subsidence, and flood damage affect structural materials most. Investigating the impact of temperature and flood damage on construction materials was the main goal of the thesis.

For flood assessment, flood loads based on the FEMA coastal construction handbook are used to simulate flooding damages and evaluate the impact on structures. Hand calculations are used to calculate the deflection. Damage evaluation involves calculations from reference cases and utilizes databases such as Hazus, the REDi rating system, and FEMA to determine recovery and repair times. The script for the assessment tool incorporates these calculations, formulas, and numbers. Eventually resulting in a graph based on the dimension of the column and the material, the deflection, damage, recovery time and repair time is returned. The current flood assessment is limited to deflection in terms of structural assessment, but it can easily be expanded to contain stress calculations or other likewise formulas.

Regarding the temperature impact, an empirical concrete corrosion formula calculates mass loss, while the Arrhenius equation assesses the deterioration of wood and steel. A specific formula for concrete corrosion considering the concrete layer is required. Using Faraday's equation, corrosion ratios or material degradation ratios can be converted into mm/year, determining the new cross-section size and assessing its impact on structural deflection by anticipating the mass loss. This loss is also directly linked to the structure's performance in a flood, effectively integrating both investigated events.

Both flood assessment and temperature effect approaches are translated into a Python script using packages like open-meteo for climate data, klimaateffectatlas for flood depths, and ifcopenshell for data extraction from IFC models. The outcomes of both scripts are presented in graphs that can be combined to illustrate the simultaneous occurrence of these events.

The script can be found on:
https://github.com/EdaAkaltun/Project-T

TABLE OF CONTENTS

INTRODUCTION

That climate is changing, and humans influence is a fact (IPCC, 2021). Whether we control and diminish greenhouse gas emissions, the current century will bite the sour apples from the past century's emissions that have led to climate change (KNMI, 2021). And if we don't lower greenhouse gas emissions, the rotten apples will also be passed down to the next generations (NASA's Jet Propulsion Laboratory, 2019). Regardless of the current research on reducing emissions, it is essential to stop for a moment and start tackling the changes already bound to happen in the present century.

It is crucial to research the confirmed changes for this century and look at it from a building perspective to start designing climate-resilient buildings to tackle the risks of climate change. Investing in climate-resilient buildings is one of the best ways to adapt to climate change, mainly because the construction sector is in the very early stages of adapting to rapid changes. The United Nations Environment Program advises that efforts must be rapidly scaled up, especially for the most vulnerable countries where most buildings are self-constructed (United Nations Environment Programme, 2021).

Even though the Netherlands is not necessarily a vulnerable country when looking at the quality of buildings, climate-resilient buildings are still of great importance because of the location of the Netherlands. But also, for the general culture of how buildings are designed: for example, A good house design in the Netherlands is bound to last 55 to 500 years (Business Insider, 2018). While with climate change, the following question would be necessary to ask oneself: would a building that is expected to last more than a hundred years from today survive the upcoming climate changes and live up to its desired life expectancy?

PROBLEM

"The construction sector is in the early stages of adapting to the rapid climate change changes, including projects in the Netherlands."

No matter how rapidly these changes may occur, climate change is not considered during design. For example, calculations are based on past averages or current values and not what will happen in the future; an examples how BENG is calculated for every building in the Netherlands (NEN, 2021). This brings risks and uncertainties regarding the design's future and whether the structure will remain unaffected. It is important to evaluate buildings' resilience in the near future.

RELEVANCE

Climate change is a topic that affects everyone. Regardless of the opinion that one holds about it, it is already happening. It is a fact that the predicted changes will somehow influence future and existing buildings to different extents. Therefore it is important to start putting these changes into the equation when designing new or maintaining existing structures.

RESEARCH GOAL

This research aims to answer what will happen regarding climate change in the Netherlands and how a building's structure will be affected by this. After that, an assessment method for these changes will be researched. Lastly, a tool will be developed to assess the changes in performance structurally that these buildings will be exposed to, considering the climate. The same tool will bring awareness to this topic (See Figure 1 Chart of the functionality of the script).

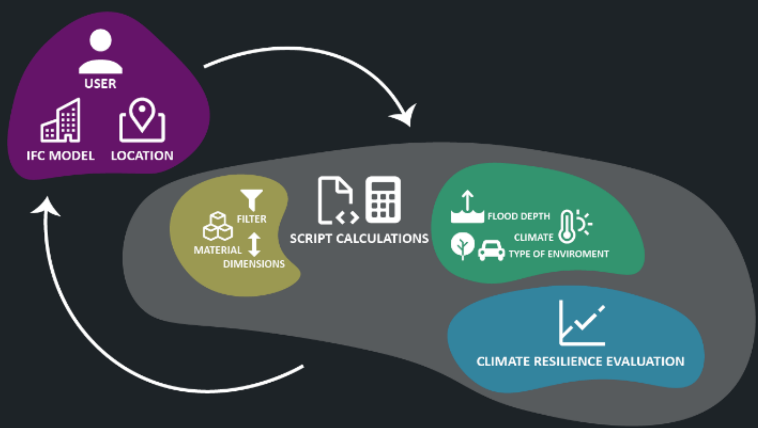


Figure 1 Chart of the functionality of the script

Questions

The following question will be answered in this report:

"How can we assess IFC models regarding their climate resilience concerning climate change in an open-source manner?"

The following definitions have been used for the main question:

- IFC models: Models according to the IFC standard.
- Climate Resilience: Ability to respond to hazardous or disturbing events in terms of climate.
- Open source: A free tool available for everyone to download and use, and the source code is publicly shared.

The following sub-questions will have to be answered to be able to answer the main question:

- *What are the key impacts of climate change on the Netherlands?*
- *How do environmental changes in the Netherlands influence structural steel, wood, and concrete?*
- *What methods can be used to numerically assess the resilience of buildings in the Netherlands to flood damage and temperature influences?*
- *How can a climate resilience assessment methodology be effectively implemented into a script using Python with open-source packages?*
- *What is an open-source approach for creating a front-end tool in Python to assess IFC models?*

Requirements

The end product needs to correspond to the following points:

- An IFC should be loaded in, and a location should be obtained.
- For the given location, predicted climate data should be loaded.
- With the loaded IFC and predicted climate data, an assessment should occur based on the materials used in the IFC on a structural level.
- The depth and assessment method of the model is closely linked to the found quantification method as a result of the sub questions in this thesis. The assessment's quality is also tied to the given timeframe for this thesis.
- The given assessment should act as support during the design process or an existing building, making the end product a design tool for climate-resilient structures.

Reference projects

- LEED Climate Resilience Screening Tool
- BlenderBIM Structural Analysis
- IFCopenshell work schedule creator
- CRCTool by Deltares

THESIS OUTLINE

This thesis will focus on the influence of climate change on the Netherlands, starting with a climate study to understand the changes occurring in the country. It will be followed by a theoretical study that limits the materials to common building materials found in the Netherlands, where the materials and their shortcomings considering the changes will be researched. Afterwards, a numerical method will be researched to calculate the direct influence of these changes on these materials. After having found the methods, these will be translated into an open-source python script and how this can be done will also be researched, this portion will serve as the script behind the interface of the tool, better known as the back end. Lastly, the interface of the tool, better known as front-end will be developed, and methods for doing this will be researched to translate the back end into a proper tool.

The practical part of the research will involve developing a tool using the information obtained in this thesis to make an open-source Python tool. The tool will allow the user to load in an IFC model and give a location to run a climate resilience assessment. The climate resilience assessment method and the front-end visually highly depend on the outcomes of the theoretical portion of this thesis. The tool will be tested by users to receive their experience with it and reflect on that.

Methodology

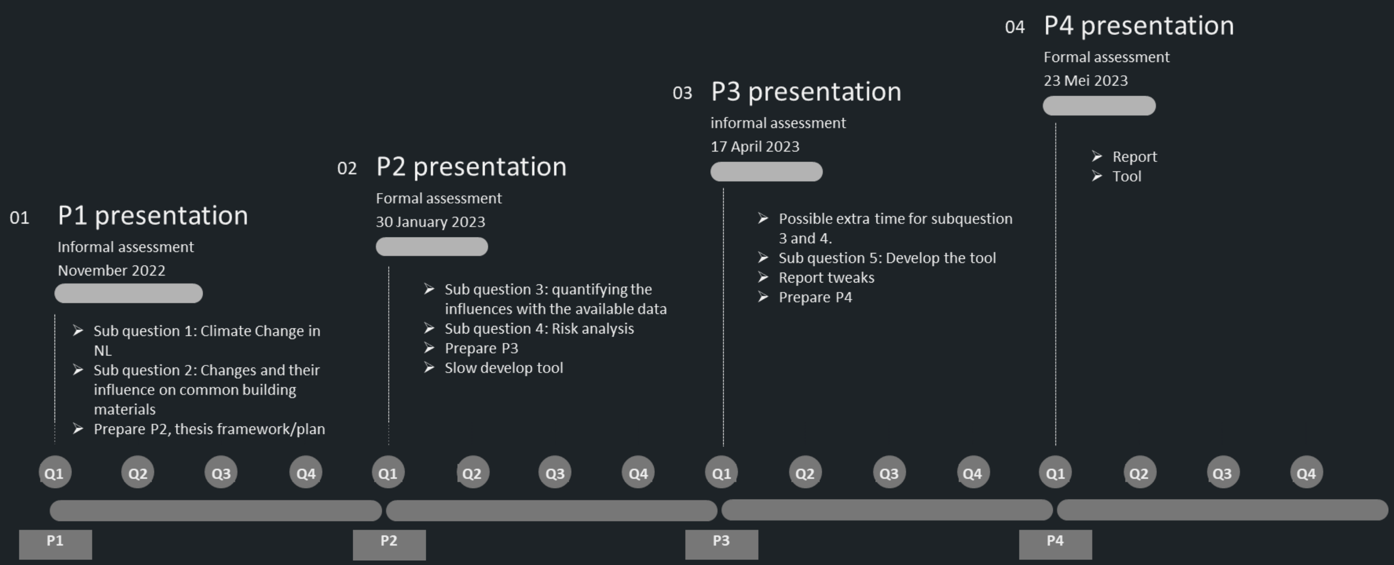
See table below.

Aspect	Detail	Method
Climate Study (subquestion 1)	Climate Change in the Netherlands based on the evaluations and predictions of KNMI.	Theoretical study based on the Dutch government's publications & existing theories on how climate works.
Material study (subquestion 2)	A material study considering occurring climate changes.	Theoretical study
Quantification study (subquestion 3)	Research on seeking methods to assess the structural performance of the materials and/or the influence on the materials from climate change numerically.	Theoretical study & possible simulations or checks
Dutch IFC study (subquestion 4)	Studying the structure of Dutch IFC models and their structure. This is according to the Dutch IFC standard. Looking for sources and/or APIs that provide necessary data for subquestion 3's outcome and working with that. Translating the method described in subquestion 3 into the back-end of the tool.	Theoretical study and/or consulting experts for relevant packages and methods. While working on the development and design of the tool directly, experimented with what works and what does not.
Tool development (subquestion 5)	Developing the tool's front end and designing it while implementing the back-end in it.	Tkinter GUI frontend development. Experimenting with the design.

Planning

See chart below.

The theoretical part will be done in P2 and P3, whereas the development and research on methods will be done towards and after P4. Repairs and finalizations with last steps will be made after P4 till P5.



CLIMATE CHANGE IN THE NETHERLANDS

This chapter will research the occurring changes in the Netherlands in light of climate change by stating observations up until now and future predictions on this matter.

OBSERVATIONS UP UNTIL 2020

According to a report from KNMI (KNMI, 2021), the following climate-related changes have been measured between 1991 to 2020:

- Temperature: The temperature has risen by 1.1°C. Spring is the season most affected by these changes, but also the season with the highest rise in temperature, the precipitation has decreased, and the number of dry days in spring has increased. This affects the growing season, which is crucial for flora and fauna.

- Decrease in frost: In the past 30 years, the number of days with frost has decreased by almost two weeks, from 65 to 53 days. And ice days have been reduced from 11 to 6 days.

- Increase in summer days: The number of summer days with more than 25°C has increased from 19 to 28.

- Increase in tropical days: Tropical days where temperatures reached more than 30C°C doubled from 2.4 to 5. The highest temperature per year has also increased by 2.4°C.

- Increase in precipitation: Very wet days have increased by a quarter. 4.3 to 5.3 days in the winter, and in summer, 1.5 to 1.9. Precipitation has not increased overall, but this is caused by decreased rainfall in spring and autumn, whereas the rain in winter and summer has increased.

- Increased solar Radiation: The Netherlands Is facing an increase in solar Radiation because of the decrease in clouds. In 2020 this was the highest so far because fewer traces from planes occurred and a decreased air pollution due to the corona measurements.

- Decrease in wind speed: Wind speed has decreased in the past 20 years, with 2%. This is likely caused by the roughness of the surface of the land due to the increase of structures/buildings. The highest windspeed for an hour is also decreasing by 3% per 10 years. Wind direction has most likely natural variations when looking at the data of the past century.

- Changes in wind direction: There is an increase in the western wind and a decrease in the east wind in the Netherlands due to the increasing air pressure above the Mediterranean area and falling air pressure north of Scandinavia. The change in wind direction has led to a decrease in cold days. This has also caused the heating of North-west Europe.

- Sea level rise: The sea level has risen with around 20 cm between 1901 and 2018. Whereas this increase in sea level gradually goes faster: between 2006 and 2018 the increase was 3.7 mm per year. Which means 4,44cm. This is almost 1/4th of the total rise that occurred in 117 years in 12 years.

- Increase in CO_2: The CO_2 concentration in 2019 was 410 ppm, the highest amount witnessed in 2 million years. In 2020 this amount increased to 412 ppm. In 2000 CO_2 concentration was only 369,8 ppm (CBS, PBL, RIVM, WUR, 2002).

FUTURE PREDICTIONS

KNMI Klimaatscenarios & Klimaatsignaal

The KNMI's Klimaatsignaal 2021 study presents an overview of the most recent scientific studies on climate change for the Netherlands and its effects nationally. According to this report, 2020 was one of the hottest years worldwide, and the Netherlands saw its first certified heatwave since 2019. It also mentions how extreme events are becoming more frequent and intense due to climate change. The report also emphasizes the urgent need for mitigation and adaptation efforts to cut greenhouse gas emissions and prepare for the effects of climate change.

Since the klimaatsignaal 2021 report of KNMI doesn't give a clear indication of the changes in a quantified manner, the Klimaatscenarios of 2014 have been considered. The Klimaatscenarios 2014 has 4 scenarios: GL, GH, WL & WH. With GL being low temperature raise worldwide and a low change in airflow patterns. In comparison, WH is a high change in airflow patterns and a high-temperature rise. GH is a great change in airflow patterns with low-temperature change, and WL is a high-temperature change with low airflow pattern change.

The Klimaatscenarios 2014 will be replaced with values from Klimaatscenarios 2023 in the end of 2023.

Sea Level & Arctic Ocean

The world average temperature of the sea and land has increased by 1.2°C in the past 9-10 years, resulting in a sea level rise of 1,2 to 2 meters in this century (KNMI, 2021).

Storage Oceans & Acidification

Over 90% of the extra energy caused by the increase of greenhouse gasses in the climate system is stored in the ocean (KNMI, 2021). This energy intake causes the water to increase in temperature, which means the sea also expands. The expansion is caused because warm water takes up more space than cold water. This expansion, next to the melting of the ice caps and glaciers, is one of the biggest reasons for rising sea levels. The intake of greenhouse gasses has also led to ocean acidification. The current ocean pH value has been the lowest in the past 2 million years.

Dutch sea levels so far

In the KNMI scenarios, the sea level rise rate off the Dutch coast is 4.9 (2.3–7.6) mm/year in 2020. This is more than 2 mm/year than the observed trend since 1993 2.8 (1.2–4.2) mm/year.

The projected differences are explainable through the changes in weather, ocean streams, regional warming, and ocean salt levels. The push-up from water through the Dutch coast in the past years has decreased, which has led to a tempered sea level rise for the Netherlands. The predictions don't consider this effect, which leads to the climate models indicating a higher sea level rise. The northeastern part of the Atlantic Ocean has warmed up less than the world average, and the salt level has also increased, negatively influencing the sea level rise.

Natural fluctuations such as these explain why the witnessed water level rises in the Netherlands do not match. These fluctuations won't be considered in future predictions because they only present a particular trend, which does not affect long-term projections.

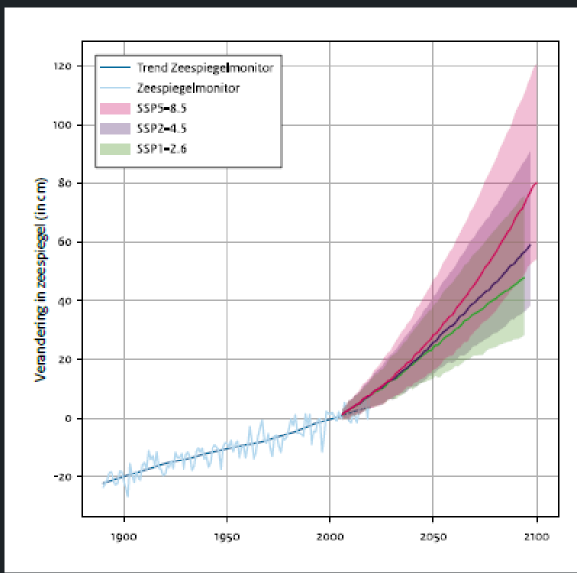


Figure 2 Sealevel rise prediction in centimeters (KNMI 2021)

Subsidence

In the Netherlands, Subsidence is a well-known major issue. It is caused by peat oxidation, clay settlement, or activities in the deeper subsurface. Peat oxidation also causes CO2 emissions and water quality issues due to released nutrients and increased brackish seepage. Ground subsidence causes underground pipes, foundations, and infrastructure damage. Uneven subsidence in urban environments increases flood risk because low levels are formed and interrupt the sewage system.

Subsidence accelerates and worsens in a drier and warmer climate. Peat oxidation accelerates at higher temperatures, and groundwater levels drop further due to a more significant precipitation deficit (drought), resulting in even more peat oxidation and settlement. When water availability decreases due to low river discharge, maintaining polder levels and thus limiting groundwater level drops becomes more difficult. As a result, shallow river discharge indirectly causes soil subsidence. Soil subsidence caused by peat oxidation is a permanent process. In the current situation, the decline can be as much as two centimetres per year and is primarily determined by the type of peat and the water level in the ditches (Stichting Climate Adaptation Services (CAS), 2023).

The most significant changes, according to Rijkswaterstaat, happened in soft soil locations where the earth has sunk by around 10 meters during the last 1000 years (Rijkswaterstaat, 2023).

The causes of Subsidence in The Netherlands are (Stichting Climate Adaptation Services (CAS), 2023):

- The draining of porous soils like peat and clay. This is done to prepare the land for agricultural or residential use. Large-scale dewatering began in the Netherlands over 1000 years ago and continues to day. Dewatering causes soil consolidation, creep, and decomposition of organic matter (peat). Consolidation refers to the compaction of saturated soil by groundwater flow after dewatering has resulted in lower groundwater levels. The vicious tendency of soft ground is referred to as creep. Lower groundwater levels allow oxygen to enter the earth. Microorganisms and mould break down organic materials under oxygen (or other chemicals), causing the soil to sink.
- Extraction of minerals from deep-lying rock, such as natural gas or salt, produces surface sinking due to compaction of the gas reservoir or the plastic characteristic of the salt in the holes created. Extraction field data can be found at the Nederlands Olie- en Gasportaal.
- Loading soft soil proceeded by consolidation and creep. The load occurs when the ground level is raised in building projects, for example, or as compensation for prior soil subsidence.

Future of Subsidence

Future subsidence is determined mainly by the rate at which the climate heats and the water level policy implemented during times. According to the Klimaateffectatlas, the Western and Northern Netherlands are the primary regions affected by subsidence in the future. Sources of Rijkswaterstaat also state this. However, there are also areas in the South and East where the subsoil is soft, and subsidence also occurs. Furthermore, Rijkswaterstaat predicts that the soil level in the Southeastern part of the Netherlands will increase (Stichting Climate Adaptation Services (CAS), 2023) (Rijkswaterstaat, 2023).

Groundwater levels

Since precipitation will increase in the Winter, according to the Klimaatscenarios 2014 of KNMI. More rainfall leads to more water supply that raises the groundwater amount, a rise in groundwater level and groundwater seepage. This increases the chances of the groundwater levels reaching a level that would cause disruptances. This is especially true for portions of the Netherlands with a low land level (Rijkswaterstaat, 2023).

Types of issues occurring due to groundwater level alterations

- High humidity in the house and mold due to wet crawl spaces or rising damp in walls
- Penetrating moisture in basements
- Soggy gardens and long-term wet green areas in the district
- Damage to urban greenery and blown down trees due to drowning of roots
- Damage to buildings due to changes in the buoyant water pressure under the foundation
- Rutting and uneven settlement of roads and pavements

The klimaateffectatlas provides datasets with chances of groundwater level complications based on the National Dutch Water model, the economic changes in terms of water usage from Deltares, and the rise of water level and precipitation from Klimaatscenarios 2014. The dataset serves as an indication of the potential water nuisance. Unfortunately, the current set lacks an indication of drainage capacities, which could highly influence the chances.

Predicted Dutch Sea Levels and its influences

A lot of permafrost areas in the Arctic areas have already been lost. The mass loss of ice caps in Antarctica and Greenland is strongly continuing. According to the climate calculation models in the sixth IPCC report with the SSP1-2.6 scenario, the temperature of the Arctic area will raise by 3,5°C., with 5,0°C. in the winter. In the high scenario SSP5-8.5 this raise will be 12°C and 16°C. And because of the melting, the ocean is absorbing more sunlight, because there's lesser surface ice that would have reflected the ice. Through the absorbing of heat of the ocean, this heat is given back to the atmosphere during the winter, this explains the high amount of increase during the winter (KNMI, 2021).

With the current progress regarding the temperature rise, the loss of permafrost areas and the mass loss of ice caps will continue. The rise of the sea level on world scale has not been felt in the Netherlands yet: the North Sea requires longer period in o
rder to determine the changes due to local effects such as fluctuations and wind in streams. The speed in which when these changes will be felt or the amount of greenhouse gasses emission determines the speed of losing these areas and mass. If the emissions are strongly reduced (SSP1-2.6), the world average sea level will be risen by 1 meter around 2150-2350. If this is not done ande continue as we are doing right now, this will happen between 2090-2140 (SSP5-8.5) (KNMI, 2021).

If experts would fail to quantify the collapse of ice cliffs, the 1-meter mark could be hit around 2070, whereas according to the current predictions it will happen between 2090-2140 with a bandwidth of 67%.

But regardless, the sea level will surely rise, even at a miraculous best-case scenario where the emissions are reduced to zero by 2050. It is predicted that this rise will continue for hundreds of years. The reason for this is that the ocean responds slowly to the global warming that has been taken place till now. Because of this, the sea level will rise after 2100 regardless of the scenarios. The KNMI also concludes that the the global sea level rise is linked closely to the sea level rise for the Dutch coast. Thus, meaning that no distinction needs to be made.

Jaar	2050	2050	2050	2100	2100	2100
Uitstoot-scenario	SSP1-2.6	SSP2-4.5	SSP5-8.5	SSP1-2.6	SSP2-4.5	SSP5-8.5
Zeespiegelstijging in cm	14-38 cm	15-41 cm	16-47 cm	30-81 cm	39-94 cm	54-121 cm
Stijgsnelheid in mm/jaar	2,8-8,7 mm/jaar	5,2-10,6 mm/jaar	5,8-12,1 mm/jaar	2,9-9,1 mm/jaar	4,4-10,5 mm/jaar	7,2-16,9 mm/jaar

Figure 3 Table with indications of sea level rise for the Dutch Coast (KNMI Klimaatsignaal 2021)

According to the most recent predictions by KNMI the best-case scenario (when we gradually emit net zero by 2050) the water levels in the Netherlands will increase by 14-28cm, whereas if the average scenario is taken this will be 15-41. And for the worst-case scenario when nothing changes, it will increase by 16-47cm (See Figure 3 Table with indications of sea level rise for the Dutch Coast (KNMI Klimaatsignaal 2021).

In the calculations for the sea level rise of the Netherlands, the factors such as the expansion of oceans due to temperature change, the self-gravitation, the mass loss of glaciers and ice caps and the changes in salt levels have been considered. These indications have a bandwidth of 90%. Previous predations predicted 15-20cm worldwide, while 20cm was the actual value that occurred (this is the highest raise in the past 3000 years). So past experiences have shown us that the higher side of the prediction should be considered.

Since 1901 the Dutch coast sea level rise was equal to the worldwide sea level rise. However, in these predictions the subsidence is considered as well. For the Subsidence in the Netherlands, an amount of 0.5 mm/year is considered by the KNMI.

When looking at the results, a high increase of the speed in which the sea level rise in the Dutch coast occurs is still not detectable due to the big year-based variations in number of storms, which greatly impact the sea level. This gives a standard deviation of yearly 6 cm, but also explains why there is a slow increase in the speed of the sea level rise. These deviations will also increase even further with climate change also influencing the number of storms.

In regards to the storm changes in the North Sea which impacts the speed up of the sea level rise in the Dutch coasts, a study has produced simulations with the past 30 years of data and the greenhouse gas increase predictions from the IPCC A2 report. According to the study's findings, the North Sea coast (Netherlands, Belgium and Germany) may experience more violent storm surges by the century's end (Katja Woth, 2006).

The sea level (thus also the rise witnessed) can locally differ due to sea streaming differences because of rotation of the earth, spatial differences in seawater temperature and salt levels. The earth's gravity field also changes due to glaciers and ice caps melting. This is because an ice mass such as Greenland can pull up the sea level locally through the self-gravitation effect. This means that melting water of the ice caps aren't distributed equally over the oceans. Locally the sea level is decreasing due to lower self-gravitation, which causes an increase in non-local areas (KNMI, 2021).

The Netherlands faces more than just sea-level rise as a result of climate change. Changes in storm surges and increased river discharge must also be factored into the country's flood protection strategy. For this, extremes surge heights have been assessed for the periods 1950–2000 and 2050–2100 (A. Sterl, 2009). In this assessment, wind speeds are projected to increase due to increased South-Western wind in the North sea. Although the Sotuh-Western wind is most increase, the NorthWestern wind is the cause of the the higher increase in surges because of the shape of the coastline of the Netherlands. This actually ensures that the extreme surge heigts in the Netherlands are unaffected by the increase in wind speed.

Greenland & Arctic influences

The Northern Sea is directly linked with other oceans, if these raise in level due to the global average increase, it will only naturally also influence the Northern Sea. The sea level of the Netherlands will also increase quicker due to the melting of the ice cap due to its direct link to the Northern Sea.

The Greenlandic and Antarctic ice caps are shrinking at an increased speed. Compared to the masses of the ice caps between 1992-2001, the mass loss of the Greenlandic icecap between 2009-2018 was seven times higher, and the Antarctic ice caps had a four times higher mass loss. Since 2018 these ice caps have continued to melt and lose mass, which will continue for the century, even if the global emission is 0 after 2050.

The loss of ice in Greenland will be mainly the melting on the surface, while in Antarctica, the melting will be caused by the relatively warm ocean water. The future of Antarctica is very unsure due to the average global warming of 2-3 compared to the pre-industrial era, which causes potential significant changes in ice streams and the ice cap's instability.
The floating ice plates in Antarctica can break in pieces this century, leading to a faster decline in land ice. For Greenland, the melting on the surface could accelerate if the jetstreams above the Atlantic Ocean will meander stronger. The jetstreams meandering will cause high-pressure zones more often during summer, leading to extreme temperatures and extra sun radiation on Greenland. Although it is still unclear if this is happening due to global warming or temporary climate fluctuations, this has happened more often in recent years.

There is also an ongoing theory on whether the disappearance of the floating ice plates in Antarctica would lead to the ice cliffs collapsing under their weight. The collapses could significantly stimulate the decrease of Antarctica. The first observations in twenty to thirty years at the

Thwaites Gletsjer in the Amundsen Sea will reveal whether this theory is false or right.

On the scale of oceans, the filling of extra water works differently than it would with a regular bowl equally (See Figure 4 Ocean gravity vs water addition behavior figure). The differences in gravity cause the melted ice caps aren't distributed equally around the world's seas. The ice masses in Greenland and Antarctica attract the sea level locally higher; when these melt, the local sea level lowers due to the decrease of the attracting effect. This area is 2500km from the ice cap (area A). When we reach area B, the sea level does rise but lesser due to the sea levels here not being pulled higher anymore due to the ice mass. Further than this, area C is an area that was never affected by the attracting effect of the ice masses, which results in an immediate increase in sea level through the meltwater.

The Netherlands is 3000km away from Greenland, resulting in the country being between areas A and B, at the exact point where the sea level change and the current sea level change are almost equal. Because of this, the influence of Greenland melting doesn't affect the sea level of the Netherlands. Regarding Antarctica, the Netherlands is in area C, resulting in a sea level rise through the climate change in the Antactic area.
So, the good news is that melting of the Greenlandic ice caps isn't affecting the sea level of the Netherlands. Whereas the bad news is that the changes in Antactica will influence the Netherlands.

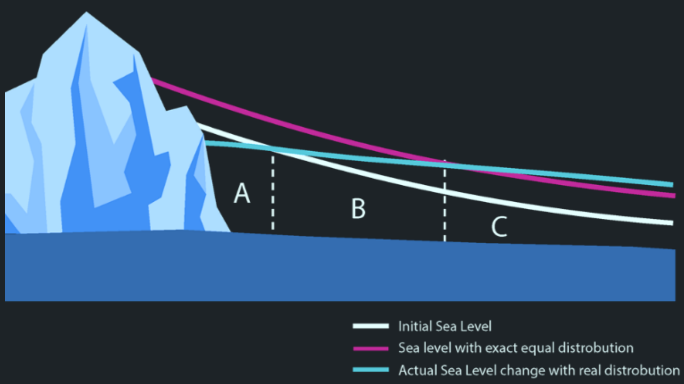


Figure 4 Ocean gravity vs water addition behavior figure

CO2 & Temperature

The CO2 in the atmosphere is rising and has never been this high. Regarding the consequences of this, a doubling of the CO2 concentration would mean that there will be a Mondial rise of temperature of 3°C (KNMI, 2021). Due to these worldwide temperature changes, the hydrological cycle (better known as the water cycle) is intensified. This causes a higher average water vapour content in the atmosphere and more precipitation with significant regional differences.

The world average temperature in 2050 will undoubtedly be higher than now, regardless of the changes that will be made in emissions now. This is because of the time that CO2 remains in the atmosphere and the amount that is also currently stored in the oceans because of the emissions in the past. Once carbon dioxide is in the atmosphere, it will remain between 300 to 1000 years (NASA's Jet Propulsion Laboratory, 2019). Injected CO2 in the oceans will stay there for hundreds of years (Bert Metz, 2005).

With the current carbon emission, the +1.5°C global heating limit set by international governments for the upcoming decennia will already be depleted in 10 years. Because of this, the sea level's slow rise is no longer stoppable (KNMI, 2021). The higher the increase in temperature, the higher the chance that the changes will become irreversible.

The increasing Arctic precipitation (through the warming of the ocean and atmosphere, resulting in more rainfall than snowfall) and the melting of the snow and land ice will make the Antarctic Ocean less salty. When this relatively sweet molten water flows toward the Antarctic Ocean, the ocean circulation will weaken, causing the warm Gulfstream to decrease. The decrease in warm streams towards the Netherlands will alter the temperature rise.

The loss of permafrost is a serious matter. Large portion Canada, Siberia, and Greenland's soil is permanently frozen. Permafrost covers 15-20% of the planet's landmass. As the planet warms, a less and smaller portion of the land freezes in the winter. According to estimations, the permafrost surface has been reduced by around 15% during the last century. According to climate simulations, another 40-75% will eventually perish depending on the degree of climate change scenarios. Permafrost produces greenhouse gases such as CO_2 and CH_4 when it thaws. The entire quantity of carbon trapped in permafrost is around 5,000 gigatonnes of CO_2, which is one hundred times the present yearly human greenhouse gas emissions. Permafrost thawing will thereby exacerbate the greenhouse effect and contribute to global (and Arctic) warming (KNMI, 2021).

Infrastructure destruction is another negative outcome. For example, disappearing permafrost is responsible for 40% of pipeline damage, with escaping methane adding to the greenhouse impact. Permafrost thawing and drying increase the chance of wildfires and extra air pollution. Finally, the retreating permafrost can unleash old infectious pathogens (due to the exposure of old bodies buried with long frozen viruses), posing public health dangers (Canadian Wildlife Health Cooperative).

While the influence and the emission of CH_4 in permafrost areas is a complex topic. The good news, is that a recent research (Christoph Keuschnig, 2022) has measured that the methane (CH_4) emission caused by the loss of a permafrost areas can be lower than anticipated. In this study, comparable methanse release from two locations in North Sweden has been analysed. In one location the permafrost loss experience started in the 1980s, whereas the other started 10-15 years later.

The difference between the two regions has demonstrated what can occur as a landscape gradually adjusts to the lack of permafrost. According to the findings, the first region to experience permafrost loss now emits ten times less methane than the other area. The spread of new plant species and the gradual drainage changes play an influence in this. This findings of this study could mean that the predicted influences on climate change by the loss of permafrost areas could be less severe than expected.

Types of CO2 emission

Natural sources of carbon dioxide emissions are ocean outgassing, decaying plants and other biomass, erupting volcanoes, naturally occurring wildfires, and even ruminant animal belches. Natural carbon dioxide sources include photosynthesis by plants on land and in the water, direct absorption into the ocean, and the formation of soil and peat (Climate.gov, 2020).

Not so natural sources of CO_2 in the atmosphere are the current new emissions from humans, but also emissions from the past generations. Due to the fact that CO_2 remains in the atmosphere for a very long period. According to Nasa CO_2 remains between 300 to 1000 years in the atmosphere (NASA, 2019). The Netherlands shares annually 0.38% of the global CO_2 emission, and this has been gradually lowering over the course of the past century (Roser, 2021).

Predicted Dutch Temperatures

Since the klimaatsignaal 2021 report of KNMI doesn't give a clear indication on the predicted temperature changes, the Klimaatscenarios of 2014 have been considered (KNMI, 2015).

The Klimaatscenarios indicate the rise, while giving the average temperature between 1981-2010 as a reference: 10.1 °C. The reference value for 2022 according to the same weather station is 12.09 °C (Koninklijk Nederlands Meteorologisch Instituut (KNMI), 2022) (KNMI, 2014).

Scenario	GL	GH	WL	WH
Worldwide Temperature Rise	+ 1 °C			
Average temperature reference (based on 1981-2010)	10.1 °C			
New average temperature De Bilt (2022)	12.09 °C			
Temperature rise in the Netherlands 2050	+1 °C	+ 1.4 °C	+ 2.0 °C	+2.3°C
Temperature rise in the Netherlands 2085	+ 1.3°C	+ 1.7 °C	+ 3.3 °C	+3.7°C

Figure 5 Table of temperature rises

Drought, Wildfires & City Heatwaves

The temperature rise through the increase of greenhouse gasses is not equal everywhere in the world. The warming up of above land goes faster than above oceans. The warming up is the strongest in the Arctic zone. Changes in airflow give regional precipitation patterns and are most likely driven by regional differences in warming. Summer temperatures and extreme heat increase substantially more locally than on the global level. The future temperature above land will most likely be proportionate to that of the global warming level, but the proportionality factor will differ amongst places. Heat extremes will occur more often, whereas cold extremes will be less occurring. Extreme precipitation will be more often in areas above land, and severe drought will also appear. According to the IPCC report, Europe's regional climate change differences can be split into four regions: North, East, Central Europe and the Middle Eastern Sea. The Netherlands is at the border of North Europe and Central Europe.

Atmospheric circulation which affects large scale wind streams is very determinant for whether the Netherlands will suffer from drought or not. Eastern winds bring dry air, which results in lesser cloud cover, which then results in a lot of solar Radiation with evaporation. While on the contrary, a Western wind would bring moist air to the Netherlands, resulting in more precipitation and thus preventing drought. Recent analysis of the KNMI show that the Netherlands will have more Eastern winds. The cause of this is 2 possible processes: Climate change decreases the speed of the gulf streams and the North Atlantic Ocean heats up less quickly than the neighboring areas, causing more frequent high pressure above the British islands. And, the strong warming of the Mediterranean

In all scenarios, the potential evaporation increases and is strengthened due to the projected decrease in cloud cover and the increase in temperature. The chances of drought occurring increase when the difference between evaporation and precipitation gets bigger.

Predicted Solar Radiation & Evaporation

The rise in temperature, solar Radiation and evaporation causes a bigger stress on areas that are densely populated. Heatwaves can be life dangering: In Spain and Portugal, between 7 and 13 july 2022, at least 238 people passed away due to the heat wave (Telegraaf, 2022).

Scenario	GL	GH	WL	WH
Solar Radiation average 1981-2010	354 kJ/cm2			
Solar Radiation rise in the Netherlands 2050	+0.6 %	+1.6 %	-0.8 %	+1.2 %
Solar Radiation rise in the Netherlands 2085	-0.5 %	+1.1 %	-0.9 %	+1.4 %
Evaporation average 1981-2010	559 mm			
Evaporation rise in the Netherlands 2050	+3 %	+5 %	+4 %	+7 %
Evaporation rise in the Netherlands 2085	+2,5 %	+5,5 %	+6 %	+10 %

Figure 7 Table of solar Radiation rises

Condensation & Pressure

According to KNMI, climate models predict that the atmosphere will warm up more than the surface temperature (KNMI, 2014). This increase in heat in the atmosphere, will cause more condensation heat: resulting in quicker condensation but also influencing the dew point. In combination with a strong temperature contract and high jet stream, low pressure can be caused due to winds at the surface converging. This low pressure also has a direct link to a higher dew point. A high humidity also plays a role in the influence of a high dew point. See figure 5 below.

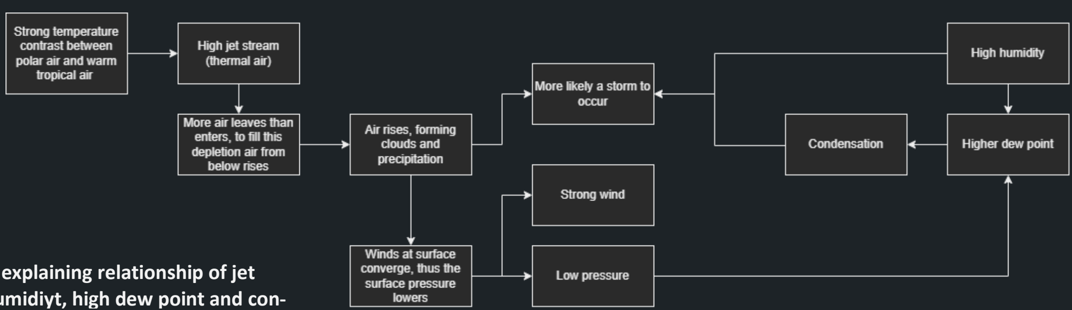


Figure 6 Graph explaining relationship of jet stream, high humidiyt, high dew point and con-

Weather

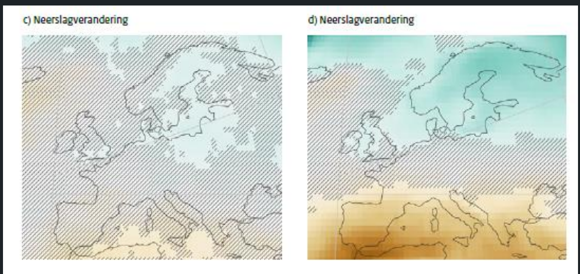


Figure 9 Precipitation changes in Europe

Regarding the weather, the KNMI predicts the following: In North Europe the precipitation will increase whereas in South Europe this will decrease (See Figure 9 Precipitation changes in Europe). When looking at the relationship of precipitation and temperature, for every Celsius +6 % rainfall will occur in the winter, whereas for the summer this is +1% to -3%.

Extreme weather

Changes in extremes have been witnessed worldwide, as extreme high air temperatures and marine heat waves (high water temperatures for a long period), intensifying of precipitation and an increase in draught are occurring more often. The biggest cause of this with a more than 95% chance, humankind (IPCC, 2021). We are getting lesser cold extremes and more hot extremes.

The polar jet stream is directly linked to the weather the Netherlands experiences. The strong warming of the Antarctic area influences the polar jet stream. The polar jet stream is a wavy stream of high-level speed winds at the height of 10km that also covers the Netherlands (See Figure 8 The jet stream over Europe (NASA)). The difference between temperatures in the polar and tropical areas affects the jet stream's strength, positioning, and waviness. The temperature rise will result in weaker streams but more substantial fluctuations, increasing the chances of meandering weather conditions and leading to more extended periods of heat, drought, cold, or precipitation (KNMI, 2021).

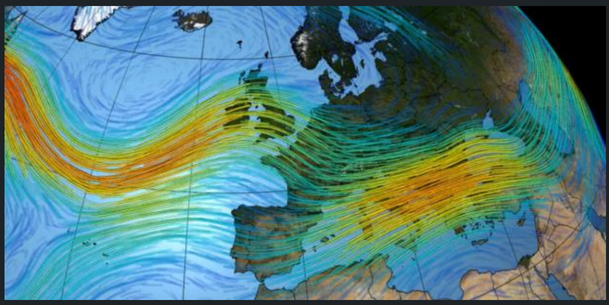


Figure 8 The jet stream over Europe (NASA)

Downburst, wind gusts, hail and thunder

Research shows that the distribution of thunder, lightning and the like is directly linked to climate change. The fluctuations of temperature and seasonal heating results in development of thunderstorms (Price, 2009).

The jet stream changes also contribute to more heavy winds such as downbursts and wind gusts.

Precipitation

The number of extremes in precipitation increased after the year 2000. With precipitation amounts of 40-50mm per hour. The days these extremes occurred are recognizable through their high dew point temperature. At a dewpoint of 18C or higher, storms are more likely to grow into bigger complex ones. Since the number of days with very humid conditions has doubled, this could be alarming.

The increase in precipitation till now is explainable by the rise in absolute moisture in the atmosphere through global warming. In the Netherlands, the atmosphere has an increasing trend in humidity. Between April and September, the increase was 8% between 1951 till 2020. The rise till now is lower than the expected 14% humid increase in case a temperature rise of 2C occurs. Between 1951 and 2020, the number of humid days (dew point above 18C) doubled.

Extreme amounts of precipitation are rising with the absolute relative humidity increase. This is true for all sorts of precipitation extremes, ranging from large-scale, multiple-day precipitation in winter to relatively small-scale, short-term precipitation in summer. In the Netherlands the relative humidity increases 3-7% per degree warming of the world average. This influences the amount of precipitation.

The relative humidity drops in the summer, and this tendency is expected to continue in the future. A decrease in relative humidity causes fewer showers and increased precipitation evaporation before it reaches the earth's surface. However, it is precisely this process of evaporation that increases the incidence of summer precipitation occurring. As a result, heavy precipitation can be accompanied by thunderstorms, hail, and strong winds in the warmer months. Summer precipitation is typically intense and brief. Because of their intensity, suddenly occurring extreme summer precipitations can significantly impact society, resulting in environmental and building damage. As has happened in Limburg in July 2021 in the Netherlands, with combination of high-water levels.

Predicted Precipitation

The KNMI has recently been able to adequately predict vertical ascents using a new generation of regional climate models with very high resolution. Making future projections more precise.

According to preliminary results from these models, the increase in severe hourly precipitation in summer showers is often smaller than predicted by the upper limit in the KNMI'14 scenarios. This reason for this is that the upper limit is based on the present climate's link between dew point and rain intensity, however according to the KNMI, recent studies has revealed that this association is overestimated.

Not all rains intensify at the same rate. Relatively light precipitation (up to 10 mm per hour) could even decrease due to the decrease in relative humidity and a more substantial influence of high-pressure areas. These changes strengthen the heavy precipitations (more than 50mm per hour). The change regarding the most extreme rainfall is according to the KNMI likely similar to the ones predicted in the KNMI 2014 Klimaarscenarios.

Any positives?

The melting sea ice is making room for socioeconomic growth. Shipping over the Arctic Ocean, for example, will rise since the Europe-Asia route via the northeast passage is approximately 40% shorter than the typical route via the Suez Canal; this is essential for ports such as Rotterdam. Tourism via cruise ships, fishing spots, and raw material exploitation (oil, gas) will also grow (KNMI, 2021).

Scenario	GL	GH	WL	WH
Precipitation average 1981-2010	851 mm			
Precipitation rises in the Netherlands 2050	+4 %	+2.5 %	+5.5 %	+5 %
Precipitation rises in the Netherlands 2085	+5 %	+5 %	+7 %	+7 %

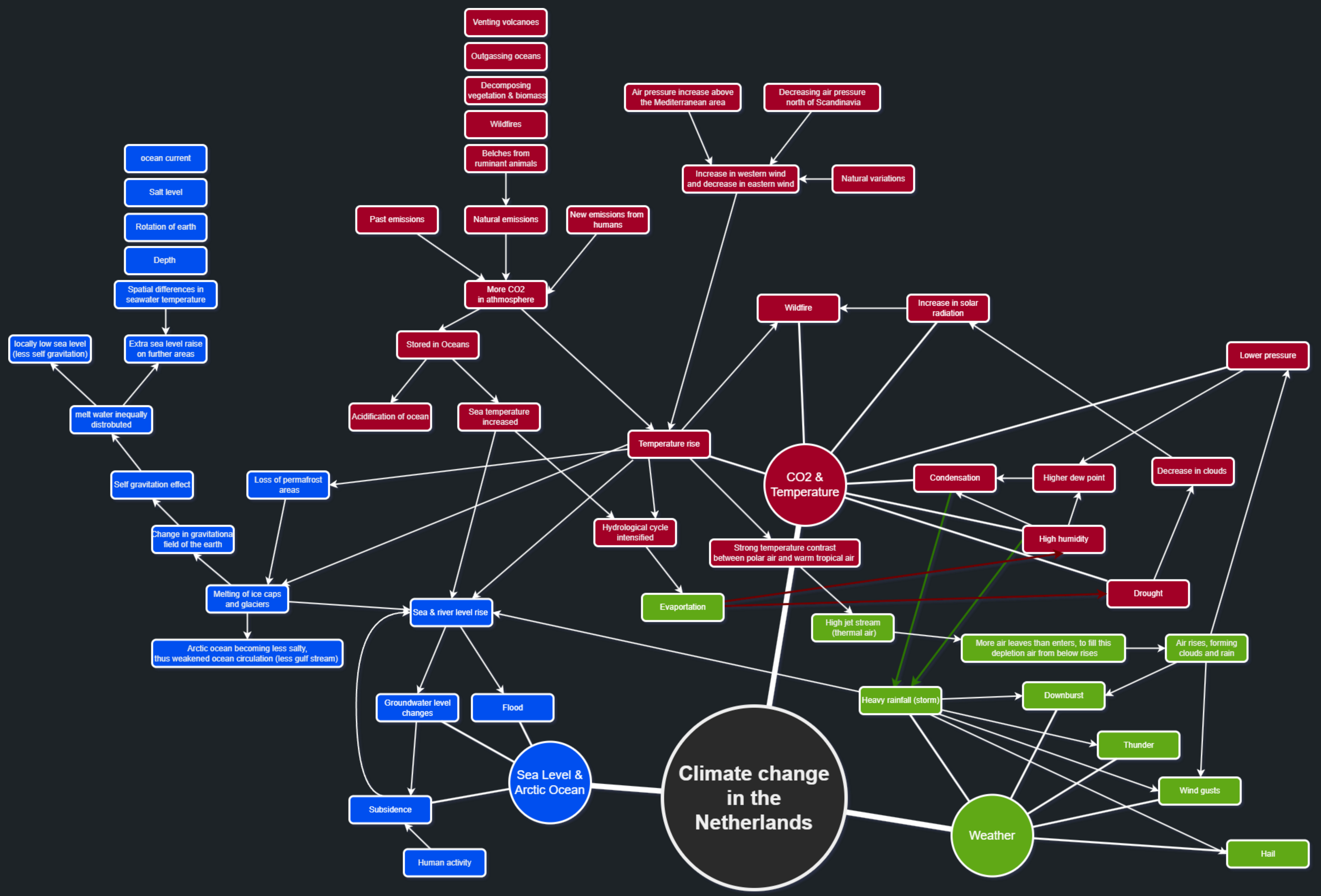
Figure 10 Precipitation values

WHAT ARE THE KEY IMPACTS OF CLIMATE CHANGE ON THE NETHERLANDS?

Below a table has been made with the conclusions based on each occurring change. The theory from the relations of why these changes occur have been translated into a figure in the next page.

Change	What happens?
Temperature	Higher temperatures due to CO_2 emissions.
Condensation	Higher dew point due to the increase in temperature & low pressure caused by Jet stream. Clouds form during condensation.
More solar radiation	Yearly decrease in clouds as confirmed by KNMI, causing more exposure to sun radiation
Low pressure	Jet Stream: Air pressure increase above the Mediterranean area & Decreasing air pressure north of Scandinavia
High humidity	CO_2 in the atmosphere causes the average temperature of the sea to increase. This intensifies the hydrological cycle, influencing the humidity of the air. The jet stream also controls moisture.
Wildfire	Lightning, the sun's heat or human activities cause wildfires. But also, when there is a long-term drought.
Drought	Airstreams influence the Netherlands' weather; when the central wind circulation is from the west, wet air will be transported to the Netherlands. It is resulting in more rainfall and wet days. When the main wind circulation is from the east, dry air is transported to the Netherlands, resulting in drought, fewer clouds and more solar Radiation.
Subsidence	Draught leads to subsidence. The ground level decreases.
Groundwater level alterations	Due to rain & evaporation. But also subsidence and the rise of seawater levels. The groundwater level can either rise or lower drastically.
Flood	Exposure to water and extreme loads. Caused by extreme precipitation and/or high sea levels.
Downburst	Intense downdraft wind load caused by storms. "These winds can easily cause damage similar to that of an EF0 (65-85mph winds) or even EF1 (86-110mph winds) tornado, and are sometimes misinterpreted as tornadoes. " (National Weather Service) -> 65-85 mph = 104-136 km/h. 86-110 mph = 138-177 km/h.
Wind gusts	Intense wind load caused by storms. Maximum wind speed in the Netherlands measured this year (2022): 114 km/h
Hail	A solid form of precipitation that can dent, shingle and gutter or crack.
Thunder	Direct strikes can cause a fire, chain failure of connected elements, and shock wave damage. It can reach up to 30 000 °C.
Storm/Heavy rainfall	Exposure to a lot of water with possible low pH levels or acid rain (acid rain isn't occurring in the Netherlands anymore).

Map of occurring changes and their cause



INFLUENCE ON MATERIALS

This chapter will research what influence the previously mentioned changes (with regards to climate change) has on building materials. Before doing so, the amount of building materials will be narrowed down to a realistic scope, and previously done similar studies will be consulted.

GENERAL INFORMATION

Although previous studies have focused on element level or overall building performance, for this research, it is essential to look deeper than just elements of a building (e.g. Foundation, Façade, Structure etc.) to quantify assessment for the tool. Thus, the research on the influence of climate change will be conducted on a material scale level and then translated into their appropriate element level (e.g., glass foundation isn't used).

Based on the results from the previous sub question, changes occur around the following three themes:

- Sea Level & Arctic Ocean changes: Subsidence, groundwater level alterations & flood.
- CO2 & Temperature increase: temperature, condensation, an increase of solar Radiation, low pressure, high humidity, wildfire & drought.
- Weather changes: Downbursts, wind gusts, hail, thunder & heavy rainfall.

Each relevant material will be discussed concerning these 3 themes and their possible influences. Common structural materials will be investigated instead of every imaginable material, considering which materials are applied in a structural context.

Previous Studies on this matter

STUDY 1

A previous study has been conducted in a corresponding theme to this subquestion. De Wilde has researched the implications of climate change for buildings. In his research. In his research, he concluded that the following aspects of a building are influenced by climate change:

- Decrease in heating and increase in cooling
- Risk that passive and neutral systems become impossible
- Heating and cooling peak loads result in inefficiency concerning HVAC capacity.
- Drainage capacity is overwhelmed, and storage and buffering needed for an increase in precipitation
- Increase in the wind influencing peak structural loads and changed frequencies resulting in different loads.
- Flooding influences and degrades building structure, system, infill, and content.

Although this is outside the scope of this thesis, it brings valuable information that could be considered in bringing into the tool regardless (De Wilde, 2012).

STUDY 2

Another study has analyzed the change in scenarios for wind due to climate change (Steenbergen, 2012).

The study stipulates that current design methods in terms of wind loads, are based on previous evaluations of the past. At the same time, it is important to consider future wind load predictions. The research also considers the conclusions from KNMI that states that there will be an annual increase of wind from -1 to +4% and mentions that this does not directly correlate to the severity of the wind gusts that may occur due to climate change.
Based on the most actual climate change model data available for now, the paper concludes that the effect of climate change suggests a change of 0.8% to +2.3% in the hourly mean wind speed with a return period of 50 years.

MATERIAL STUDY

Building Materials

As mentioned before, common materials will be investigated to make the scope of this research realistic.
In a very thorough report by Matabolic, SGS and Economisch instituut voor de bouw, it has been made clear that the most common 8 materials in the Netherlands are the following (Jelger Arnoldussen, 2020):

Concrete, Steel, Brick, Wood, Insulation, Glass, Sand, and Stone (Ranked from left to right, with the left being the most used)

Regarding the structural theme of this thesis and the time limit, the building materials that will be investigated are Steel, Wood and Concrete, with an addition of glass since most of the buildings, regardless of their structural material, contain glass. These few materials can cover most of the buildings in the Netherlands.

Concrete

Concrete can fail in a lot of ways. The LCETED (Institute for civil engineers) has listed the following (LCETED INSTITUTE FOR CIVIL ENGINEERS, 2021):

- Chemical Reactions: Acidic reactions, Aggressive water, alkali-silica reaction, sulfate situations/attack
- Unintentional loads: uncommon loads that occur accidentally, such as earthquakes.
- Poor workmanship
- Corrosion: Corrosion of the steel reinforcement in concrete.
- Design errors
- Abrasion: mechanical degradation due to grinding, impact, overload, crush, and friction
- Cavitation: Cracks on concrete surfaces occur due to negative pressure zones in water flow, collapsing water vapor. The impact results in very high pressure in a small area.
- Freezing and thawing: water fills voids of concrete and then freezes, which results in expansion.
- Settlement and movement: Movements due to subsidence or other movement-related actions. Concrete rigidness cannot withstand this and cracks or spalls.
- Shrinkage: Hot and windy days result in moisture loss in concrete, which causes shrinkage.
- Fluctuations in temperature: concrete expansion when it's hotter and contractions when it's cooler.

To evaluate the ways of failure in light of the concluded climate change themes, each way of failure has been evaluated for each climate change aspect in the Netherlands, as concluded in the first sub-question.

Subsidence & Groundwater level changes

The sinking or settling of the ground over time can cause damage to concrete structures. This is because the movement of the ground can put stress on the concrete, cause it to crack, and tilt the structure. The tilting can damage the steel reinforcement inside the concrete due to unexpected movements, making the concrete more prone to cracking and failure. But also, directly cause an imbalance in the structure (AXA UK, 2022).

Exposure to excessive groundwater levels can harm concrete foundations specifically, which can be proven by Terzaghi's general bearing capacity equation. This equation takes the weight of the soil into the equation, which involves the unit weight of water but also the weight of the soil (Structville Integrated Services, 2021). The soil beneath the foundation can become saturated due to groundwater level changes, resulting in increased pressure and cracking, buckling, and other structural issues. Furthermore, water can seep into the foundation, damaging the concrete, reinforcing steel corrosion, and other commonly known steel and water exposure damages. On the other hand, low water levels can cause the soil beneath the foundation to become dry and compact, which then again influences the foundation's load-bearing capacity, which is caused by the change in the amount of support provided to the foundation by the soil. This change can cause the foundation to settle unevenly, leading to cracking and other structural damage. Apart from all this, low groundwater levels can cause the soil to become more acidic, leading to corrosion of the reinforcing steel and other damage to the concrete. Proof of this is that the Rijksoverheid has stated that the soil in the Netherlands is becoming a little more acidic (Rijksoverheid, 2021).

Flood

Flooding can significantly impact concrete structures due to potentially prolonged submersion causing the reinforcing steel to rust, reducing the strength of the concrete, and making it more prone to cracking (because water can increase the pressure on the concrete, causing it to flex and move, leading to the formation of micro-cracks, which can then spread and grow over time). Freezing temperatures can cause the water inside the concrete to expand, leading to further cracking and porosity. Floodwaters can also cause scouring and erosion of the surface (LCETED INSTITUTE FOR CIVIL ENGINEERS, 2021), removing the protective layer and exposing the reinforcing steel. Chemical reactions may occur if the floodwater contains high levels of dissolved salts, acids, or other substances, leading to further damage (Structural Guide, n.d.). Finally, the potential harms that can come with the great force of a flood cannot be left out in this matter.

Increased temperature

High temperatures can expand concrete structures, which can cause cracking, spalling, and delamination of the surface of the concrete. It can also lead to a loss of compressive strength, making the structure more vulnerable to failure. Additionally, rapid evaporation of the water inside the concrete can increase the risk of cracking and impede proper curing. Internal cracking can also occur, like when concrete is in prolonged submersion in water, weakening the concrete's structural integrity. Further, the reinforcing steel can expand, leading to cracking and rusting and reducing the strength of the concrete. Finally, high temperatures can accelerate the Alkali-Silica Reaction (ASR). This chemical reaction occurs between the alkali cement and the silica content of certain types of aggregate, causing the concrete to expand and crack (LCETED INSTITUTE FOR CIVIL ENGINEERS, 2021) (Bernice Mizzi, 2018).

Condensation

Condensation can have a detrimental effect on concrete structures. It can cause the reinforcing steel inside the concrete to rust, reducing the strength of the concrete and making it more susceptible to cracking and failure. Additionally, it can help create an ideal mold growth environment (Polygon, n.d.). Furthermore, suppose the condensation freezes (When temperatures drop below freezing, the water vapor in the air can condense and freeze on surfaces). In that caseit can cause freeze-thaw damage, leading to cracking and deterioration of the concrete surface (LCETED INSTITUTE FOR CIVIL ENGINEERS, 2021).

Increase in solar Radiation

High solar Radiation can lead to various detrimental effects on concrete structures. Heat expansion might cause fracturing, flaking, and separation of the surface andhe development of small surface cracks due to temperature shifts (Semenenok, 1969). In addition, the heat can result in a loss of the material's compressive strength, which can undermine its stability. To add on, the elevated temperatures can cause the water inside the concrete to evaporate more quickly, resulting in cracking and preventing the concrete from curing properly. Lastly, the heat can cause the reinforcing steel within the concrete to expand, leading to rusting.

Low pressure

The impact of low-pressure environments on concrete can be quite damaging. According to a study, low air pressure has been found to affect concrete's compressive strength and durability, as well as its permeability, deicer salt scaling, water variation, and water absorption, particularly after 28 days (Xin Ge, 2018).

Another study has found that low-pressure environments have proven to reduce the strength of ultra-high-performance concrete. Especially the compressive strength significantly after 28 days and 60 days. Low-pressure areas also affect pore structures, resulting in lower average pore diameter and porosity. The low pressure and low humidity helped in the water loss of the concrete, eventually leading to the compressive strength being significantly lower (XIONG WU, 2021).

High Humidity

High humidity can harm concrete structures. Curing can be slowed down, which can be beneficial in ensuring a more even and stronger product. Too much moisture in the air can lead to shrinkage and cracking in concrete. Furthermore, the reinforcement steel can rust, reducing its durability and strength. Lastly, mold and mildew can grow, compromising air quality and weakening the structure of the concrete (LCETED INSTITUTE FOR CIVIL ENGINEERS, 2021).

Wildfire & drought

Drought can influence existing concrete structures but also on similar materials like concrete. The lack of moisture can cause shrinkage and cracking andurface cracking on large concrete surfaces (Lu, et al., 2011). Existing cracks and joints can widen, putting more strain on the structure and making it more vulnerable to failure.

Downbursts & wind gusts

Wind gusts can bend and flex concrete structures, leading to cracking. Vibrations can also cause fatigue and cracking over time (Carvalho, 2019).

Hail

Hailstones can harm concrete structures by weakening them and making them vulnerable through chipping, cracking (D.A. Paterson, 1994), and spalling the surface, forcing water into openings, and eroding the surface.

Thunder

Thunderstorms can cause damage to concrete, causing cracking, spalling, and expansion and contraction. The extreme heat of the lightning discharge causes rapid expansion that leads to cracking
(Lanser, Amde M. Wolde-Tinsae, & and Lowell F. Greimann, 1984). This cracking can also leave the steel rebar open, leading to more complications.

Heavy Rainfall

Heavy rainfall can cause a variety of issues with concrete structures. Heavy rainfall can cause surface corrosion, leading to pits, divots, and uneven surfaces. Suppose the concrete is exposed to repeated freezing and thawing cycles. In that case, the water in the concrete can expand and contract, causing cracking, worsening existing damage or flaking (Hansson, 2011). Heavy rainfall can also cause water to seep into the concrete, potentially leading to leaks and, worst-case flooding. Scaling, when the surface of the concrete peels off in thin layers, can also occur due to weathering and freeze-thaw. Lastly, suppose the concrete is already damaged. In that case, heavy rainfall can cause water to penetrate the concrete and reach the reinforcement steel, potentially leading to a higher corrosion rate and, thus, weakening the structure (LCETED INSTITUTE FOR CIVIL ENGINEERS, 2021).

When it comes to the mechanical properties of concrete, even if short exposure to heavy rainfall negatively affects concrete's mechanical properties and microstructure, the results of research on this matter show that short-term heavy rainfall can reduce the Compressive strength, splitting tensile strength and shear strength of concrete by 50, 70 and 37%. The decline of the concrete microstructure is caused by the increase of the water-binder ratio of concrete, and the short-term heavy rainfall influences that (Wei-Jia Liu, 2022).

Suppose a concrete structure is already damaged. Heavy rainfall can cause water to penetrate the concrete reaching the reinforced steel, resulting in more complications. If this water also freezes, it can cause the expansion of cracks: worsening the damage that was already there. Especially since free-thaw cycles are the most common conditions that significantly impact concrete's durabilit (Zhang, et al., 2022).

Wood (Timber)

An analysis of causes for timber structure failure has concluded that the most frequent reason for failure is due to flaws in or a lack of strength design (41.5%), which is followed by bad construction principles (14.1%), on-site adjustments (12.5%), and inadequate or no design concerning environmental measures (11.4%). Around half of the failures are the fault of the designer, and roughly one-fourth are the fault of the construction site workers. Only a tiny portion of failures (around 11%) are attributable to timber quality, production techniques, and principles (Hansson, 2011).

Since the main cause of failures are revolved around the designer, it is important to be aware of the possible consequences of climate change on the performance of timber.

Subsidence & Groundwater level changes

Subsidence and groundwater level changes is a well-known complication for timber. Three elements have been identified that significantly affect the quality of timber pile foundations based on a dataset of hundreds of analyzed structures in the Netherlands: a fall in the groundwater level, excessive pile loads, and timber rot under water (KLAASSEN, 2015).

Another study has concluded subsidence can cause timber pile degradation; the key trigger for this hazard is the low groundwater level (Deltares, 2020).

Groundwater levels significantly influence timber structures. According to a report published by Deltares, it is confirmed groundwater levels will decrease, and this will drastically influence buildings on timber pile foundations or steel. The foundation's soil becomes dry and compacted when the water levels drop. This causes the soil to shrink and pull away from the foundation, leading to the settling or shifting of the structure. Much previous damage has been witnessed and reported; the changes will only make this occurrence more frequent (Deltares, 2020).

Flood

Flood's impact can damage and even break timber structures, including other building components such as glass, especially because timber is relatively weak to impact loads compared to concrete and steel. Timber structures are also more vulnerable to flood damage than other building materials. This is because timber is generally porous (Sundararaj, 2022) (While steel is not): when it absorbs water, it becomes swollen and distorted. Timber can also decay and rot when exposed to moisture for a long period.

Because of this, flood can cause the timber structure to shift or settle, leading to cracks in the foundation and walls and uneven or sagging floors. Additionally, the increased moisture can cause rot and decay in the timber structure, weakening it and making it more susceptible to damage (Lamond, 2017).

According to the Centers for Disease Control and Prevention, floodwater can also contain chemicals, sewage, or other harmful substances, increasing the risk of the structure and humans being harmed even further (U.S. Department of Health & Human Services, 2022).

Increased temperature

As the temperature increases, the moisture content of the timber decreases, which can cause the timber to become more brittle. Also, high temperatures can cause the timber to expand, leading to warping and other damage that can decrease its load-bearing capacity. Higher temperatures have also proven that the bending strength of timber is influenced (Sundararaj, 2022)

An increase in temperature can also make it more likely for wood-eating organisms to manifest, promoting plant growth on the timber and leading to further deterioration. Generally, timber is advised to be kept dry and away from wood-eating organisms. This way, even timber artifacts have been recovered in the past (Mindess, 2007).

Condensation

Condensation can influence timber in several ways. The surface fibers may loosen and wear away due to cycles of shrinking and swelling when the timber is dried and rewetted (note that this would be in combination with drought or humidity changes), as well as occasionally due to cycles of freezing and thawing, which can result in a very gradual surface erosion which is merely about 6 to 12 mm per century (Mindess, 2007).

Increase in solar Radiation

Timber suffers from photodegradation when exposed to increased solar Radiation for some time. This can lead to a failure of the timber coating that is necessary for protection. An experiment has proven that ultraviolet light degrades timber, and other than ultraviolet light, also contributes to the loss of strength (Derbyshire, 1981).

Low pressure

No sources have been found on this matter. Yet, low pressure influences the aspects that impact timber performance. The air can hold moisture when pressure is lowered, leading to higher relative humidity. The impacts of higher humidity are discussed in the other theme, such as condensation and increased rainfall.

High Humidity

High humidity can severely influence timber. The fiber saturation point for timber-destroying fungi is above 25-30%. Properly air-dried timber has a moisture content of less than 20% (Mindess, 2007).

A higher humidity amount can cause timber to increase in moisture content due to hygroscopic timber (Hardwood Distributors Association, n.d.).

Bacterial growth may also occur when the moisture content of timber is high enough, causing a significant loss in strength. Some bacteria can even influence the permeability and absorptivity of timber, making the degradation process even faster (Mindess, 2007).

According to timber and climate change research, the most challenging property is the moisture content (Anikó Csébfalvi, 2020).

Wildfire & drought

Timber is a highly flammable material, yet timber structures have proven to have some fire resistance due to timber being a good insulator and dropping the internal temperature when inflamed on the surface. The ignition temperature for timber is estimated to be around 200 ◦C. The exposure duration of the heat influences the ignition temperature significantly: timber ignites at 30 minutes of 180 ◦C exposure, 2 minutes exposure of 300 ◦C and less than 30 seconds if the temperature is 400 ◦C (Mindess, 2007).

Drought can affect timber positively. Timber can easily exchange moisture with the atmosphere-leading to a moisture equilibrium with its surroundings (Mindess, 2007). Timber is at a fiber saturation point of around 25%, which is the point where the timber starts shrinking or has a sudden increase in compressive strength (BARKAS, 1935).

Downbursts & wind gusts

Extreme wind loads have been proven to be catastrophic to timber. The most common forms of damage to timber structures by hurricanes or thunderstorms are the removal of roofs, broken doors and windows, removal of roof sheathing, and rigid body rotation (Rosowsky, 2002).

The same study also concluded that performance problems are not always caused using timber in projects subjected to high wind loads. According to the report, the bulk of performance problems is caused by improper engineering of the vertical load path, including the interaction and relative contributions of structural and non-structural elements and assemblies, and ensuring the integrity of the building envelope (Rosowsky, 2002).

Hail

Hail can damage timber exposed to it, especially when it comes to the thin layers of external systems. The most common damage is on timber roofs caused by strong winds and hail. It has been reported that hail impact has resulted in poor performance of roof coverings (Kramar, 2015).

Thunder

The heat of lightning can cause the burning of timber. Research has been conducted on much previous centuries' evidence of timber structures hit by thunderstorms. Timber with a higher humidity content cracked more easily, with greater damage and damage area. On the other hand, dry and low-density timber was easier to burn. Thick timber was more difficult to be damaged by thunder (Li, 2021).

Heavy Rainfall

The moisture content of timber determines its structural performance of it. Since climate change results in moist-related consequences such as a higher temperature, more rainfall, and higher moist levels, it severely influences the potential of timber structures when exposed to it. Heavy rainfall can cause water to be absorbed by the timber, eventually leading to damage from swelling, shrinkage, cracking, and deformation (Anikó Csébfalvi, 2020).

Steel

According to the British Welding Research Association there are six failure mechanisms for steel:

- Excessive plastic deformation from Static load or impact
- Instability
- Creep
- Stress corrosion
- Fatigue
- Brittle fracture

Fatigue is the most common cause and brittle fracture the most striking (Weck, 1965).

Subsidence & groundwater level changes
Research with simulations of steel structures suggests that steel structures are suitable in terms of ductility for subsidence. The computer simulations revealed that the structure could withstand angular distortions without suffering notable damage. The research further suggests that cold-formed steel structures can minimize damage from subsidence and should be used for structural safety in areas with great ground settlements through subsidence (Missouri University of Science and Technology, 2016).

As stated in the timber chapter, steel is exposed to the same risks as timber regarding groundwater level changes when it comes to the foundation. Even though the structure can withstand deformations, buildings with steel foundations still suffer in the Netherlands due to groundwater level changes resulting in subsidence (Deltares, 2020).

Flood
Flooding causes three key issues: flood duration (material submerging), high velocity and flood-borne debris and degradation of the materials (SFIA, 2018).

In terms of the flood borne debris, a study researching to calculate the debris on building structures has concluded that multiple impacts from a debris cannot be captures by a single debris impact formula, resulting in the calculation of this matter being complicated (Jacob Stolle, 2018).

Another study has simulated a steel-bolt-connected steel frame exposed to hydrodynamic force and has concluded that a downscaled frame resisted a hydrodynamic force of 62.3 kN and has shown no indication of broken connections or failure. Proving that it has good capability to perform well against high-impact pressure due to its strength and ductility performance. The study also concluded that this steel-bolt-connected design is feasible in prone to flooding zones (Auwalu, et al., 2022).

This proves that steel can be a very applicable material as a structure against flood.

Increased temperature
The effect of temperature on atmospheric corrosion is a complex concept. The corrosion rate depends on ambient temperature, which is related to the Arrhenius law (Minh N Nguyen, 2013).

A general rule of thumb has been believed that a 10 C increase in temperature will double the corrosion rate (Corrosion Doctors, 2012).

But in reality, this would only be the case in a stable condition with constant high humidity levels and within a normal range of temperatures such as 20-30 C (Roberge, 2000).

Making atmospheric corrosion a complex process can only occur when a moisture layer is on the metal surface. When the relative humidity rises, and the temperature falls, a moisture layer develops, causing corrosion processes on the metal surface. Whereas when the temperature rises and the relative humidity falls, the moisture layer evaporates, and the corrosion processes end due to lack of surface moisture. Because of this process, the influence of temperature on air corrosion is a secondary aspect (Cole, 2010).

Yet, just like many more studies, a study has found that temperature can promote stress corrosion and the corrosion rate of a particular type of stainless steel (Yawei Lu, 2020).

Leaving the relationship of temperature and corrosion a complicated matter that cannot be narrowed down to one answer.

Condensation
Steel is very corrosive. Corrosion causes loss of strength and stiffness in concrete structures (Mark G. Stewart, 2019).

Although steel can be produced in a corrosion-resistant manner through chromium content acting as a protective layer together with oxygen, it is still prone to corrosion. Over time, when not maintained, stainless steel can rust. Stainless steel is still prone to general, galvanic, pitting and crevice corrosion (thyssenkrupp, n.d.).

Steel is very resistant to mold forming because it is an inorganic material. Mold development is expected in buildings when materials are submerged in floods or moisture for an extended period. Steel is also one of the few materials that are resistant to termites. The good news is that steel does not absorb water like wood, making it an excellent structural material for moist environments in these aspects (SFIA, 2018).

Increase in solar Radiation

Solar Radiation has a very clear significant influence on the performance of steel. According to a study that focuses on the influences of solar Radiation and similar temperature influences on steel, it is concluded that temperature variations caused by non-uniform temperature variations, solar Radiation included, should be considered in the structural design (Xu, 2020).

This is because many studies have proven that temperature differences within structures are sincerely non-uniform (Meng Zhou, 2020,), this is correlated due to the intensity of solar Radiation.

Also, in a case study, based on long term data, the maximum temperature of Yujiabu Railway Station Building under strong solar Radiation has been proven to be more than 18 °C compared to the rest of the structure (Zhongwei Zhao, 2016). A significant difference in temperature was also the case for the indoor water recreation project Tien Rice Cube, where the steel members under the glass roof showed a structural temperature difference of of 24 °C at noon in summer (Hongbo Liu X. L., 2015)

Another study has concluded that thermal stress and deformation that is caused by this temperature difference due to non-uniform temperature fields (with solar Radiation included), is more severe than consequences that come with traditional uniform temperature loads (Hongbo Liu Z. C., 2012).

A study simulated the effects of non-uniform termal load of Caofeidian Coal Storage (an aluminium dome), and concluded that the maximum nodal displacement is 80.4 mm and the maximum member stress 68.9 MPA, which are 42.65% and 55.21% higher than the calculation results when only considering atmosphere temperature variation (Hongbo Liu Z. C., 2014).

High Humidity

Steel is dimensionally stable in moist environments; it does not warp, preventing any risk of damaging materials around the structure, such as walls and floors (SFIA, 2018).

The problem that is tied to high humidity is that it is the most important factor in atmospheric corrosion due to moisture (Corrosion Doctors, 2012).

High humidity influences the corrosion rate due to the increase in surface wetness; the moisture layer on steel forms at a relative humidity above 80% and a temperature above 0 (Minh N Nguyen, 2013).

When steel corrodes, the corrosive reaction causes a change in the microstructure of the steel's surface, making it brittle and flaky. This way, steel loses its mechanical strength and elasticity, severely impacting the structure's lifespan.

Wildfire & drought

Drought positively influences steel due to humidity playing a role in corrosion. Steel isn’t a fire resistant material, making it vulnerable to wildfire if not treated.

Downbursts & wind gusts

The combined effects of changes in sea temperature and wind speed could cause a change in DMS flux to the atmosphere of 2–8% under doubled carbon dioxide (CO_2) conditions.
Changes in wind patterns may affect the generation of marine aerosols, while changes in atmospheric moisture will affect the formation of sulphate aerosol and acid rain (Paterson, 2010).

Thunder

Metal buildings are not more prone to thunderstorms than other materials, this is a misconception. The tallest object in the area is what lightning is attracted to.

Since steel is a conductor, the damage from thunder is less than other materials that aren't (National Steel Buildings, n.d.).

Heavy Rainfall

Corrosion does not develop with low concentrations of water (Vagapov, 2020). Yet, precipitation can cause the washing away of atmospheric corrosive pollutants, which reduces the corrosion rate (Corrosion Doctors, 2012).

Although rain can be beneficial, long exposure to precipitation can cause hydrogen embrittlement on steel. Hydrogen embrittlement is the loss of elasticity and load-bearing capabilities of a metal caused by the absorption of hydrogen atoms or molecules by the metal. As a result of hydrogen embrittlement, components crack and shatter at stresses lower than the metal's yield strength (Industrial Metallurgists, LLC, n.d.).

A study conducted on Australian cities on what the change for corrosion rates will be with regards to climate change, has concluded that for a city where the humidity and temperature increases, the corrosion rate will be increased by 14% for both zinc and steel (Minh N Nguyen, 2013). And in this matter, rainfall has proven to be the strongest environmental matter in atmospheric corrosion (Zibo Pei, 2021). The same paper also suggests an increase of 10% above the 14% due to rainfall.

Findings

- Due to low pressure (on earth), influences on materials proved challenging to find reference research on.
- Rare events (such as thunder, hail etc.) become more severe. While the influence of them becoming more severe directly on the materials is hard to be told because these changes aren't directly quantified or easily predictable.
- Temperature and humidity are the clear, most impactful weather-related events.
- Subsidence and flooding are the most impactful events, next to wildfire/thunder (but fire safety is already considered due to building law.

HOW DO ENVIRONMENTAL CHANGES IN THE NETHERLANDS INFLUENCE STRUCTURAL STEEL, WOOD, AND CONCRETE?

The change in condensation can strongly influence steel, wood and concrete because steel is very corrosive. For concrete, an increase in condensation causes mould growth environments; for timber, the surface may be prone to erosion due to freezing. But these occurrences are in particular different climate environments for each material.

With regards to the increase in solar radiation for steel, this has a clear impact due to previously conducted research proving that solar radiation can significantly influence the structural performance of steel. For concrete and timber, this is less severe but also problematic due to local expansions or photodegradation and coating failure.

Not much information was found regarding low pressure, and low pressure is a more complicated change due to it influencing everything but not directly influencing itself.

High humidity influences all the materials. For steel, this is the increase in corrosion rate due to surface wetting, whereas, for timber, this is due to the increased moisture. This can cause slowed-down curing for concrete, which is actually a positive thing for concrete hardening.

Drought positively influences timber and is harmful for concrete due to cracking.

Increased temperature influences all the materials but remains complicated because the relationship between temperature and corrosion is disputed. The temperature can be favourable for timber due to lower moisture values, but wood degradation will be increased. For concrete, potential cracking can occur but also influences corrosion.

Groundwater level alterations and subsidence influence the materials indirectly due to shifting of the structure, which in return may cause extra stress on the structure, causing cracking.

Steel is resilient in the event of flood because it is an inorganic material, but the matter is whether steel would survive the impact loads. This is a serious matter because timber is weak to impact load and also prone to weakening due to exposure to moisture. Concrete can have rusting issues due to prolonged submersion and is also not the best in impact loads due to it being brittle.

Downbursts and wind gusts do not seem to influence the materials significantly but is more a matter of adequately designing the structure.

Hail & thunder are directly damaging and chipping events for each material. In comparison, storms and heavy rainfall influence moisture content.

Based on the table that can be found on the next page, two changes/events were chosen to proceed further. This was also discussed during the P2 graduation thesis presentation of TU Delft with the respective supervisors. The findings in the table suggest that flood, precipitation, subsidence, and temperature are the most relevant (for this thesis) events to be investigated first out of all listed. Based on the predicted damage severity if the event were to occur and the chance that it can happen. Out of this presentation, it was concluded that flood damage and temperature would be the two events that would be researched further.

Table of material influences

Change	What happens?	Material	Influences	Damage severity	How to evaluate
Condensation (geodataframe from klimapedia)	Higher dew point due to the increase in temperature & low pressure caused by Jet stream. Clouds form during condensation.	Steel	Steel is very corrosive. Corrosion causes loss of strength and stiffness in concrete structures. Due to being an inorganic material, it can withstand issues like termites and it also does not absorb water like timber does.	High	Steel corrosion can be calculated
		Timber	The surface fibers may loosen and wear away due to cycles of shrinking and swelling when the timber is dried and rewetted (note that this would be in combination with drought or humidity changes), as well as occasionally due to cycles of freezing and thawing, which can result in a very gradual surface erosion which is merely about 6 to 12 mm per century.	Medium	Equilibrium Moisture Content Formula
		Concrete	Creates ideal mold growth enviroment, but increases chances of rusting of the reinforcement. May also cause free-thaw damage.	Medium	Model for the evolution of concrete deterioration due to reinforcement corrosion?
Increase in solar radiation (klimaatscenarios)	Yearly decrease in clouds as confirmed by KNMI, causing more exposure to sun radiation	Steel	Solar radiation has a very clear significant influence on the performance of steel. According to a study that focuses on the influences of solar radiation and similar temperature influences on steel, it is concluded that temperature variations caused by non-uniform temperature variations, solar radiation included, should be considered in the structural design.	High	Solar radiation can be calculated
		Timber	Photodegradation which can lead to coating failure. If the coating is necessary for protection this can be problematic. Ultraviolet light also degrades timber which can cause loss of strenght.	Medium	Solar radiation can be calculated
		Concrete	Local heat expansions & evaporation of water inside the concrete. The local heat can also cause the reinforcement to rust.	Medium	Solar radiation can be calculated
Low pressure	Jet Stream: Air pressure increase above the Mediterranean area & Decreasing air pressure north of Scandinavia	Steel			
		Timber		Low	
		Concrete	Damaging to concrete that needs to heal, reduces the durability and compressive strenght.	High	
High humidity (klimaatscenarios)	CO_2 in athmosphere causes the average temperature of the sea to increase. This intensifies the hydrological cycle, influencing the humidity of the air. The humidity is also influenced by the jet stream.	Steel	High humidity influences the corrosion rate due to the increase in surface wetness; the moisture layer on steel forms at a relative humidity above 80% and a temperature above 0. When steel corrodes, the corrosive reaction causes a change in the microstructure of the steel's surface, making it brittle and flaky. This way, steel loses its mechanical strength and elasticity, severely impacting the structure's lifespan.	High	Steel corrosion can be calculated
		Timber	High humidity is problematic for timber because it increases the material's moist content, but also creates a good enviroment for timber-destroying fungi or bacteria. According to a research the biggest challenge for timber in light of climate change.	High	Equilibrium Moisture Content Formula
		Concrete	Slowed down curing (can be positive). Rusting of reinforcement and growth of mildew on concrete.	Medium	Model for the evolution of concrete deterioration due to reinforcement corrosion?

Wildfire & Drought (geodataframe from klimapedia)	Lightning, sun's heat or human activities cause wildfires. But also, when there is a long-term drought, which will be the case with climate change.	Steel	Moisture doesn't impact steel directly but humidity influences corrosion rates. Steel is vulnerable to fire.	Medium	
		Timber	Drought can positively influence timber. Yet timber remains high flammable.	Medium	Equilibrium Moisture Content Formula
		Concrete	The lack of moisture can cause shrinkage and cracking and surface cracking on large concrete surfaces. Existing cracks and joints can widen, putting more strain on the structure and making it more vulnerable to failure.	Medium	
Increased temperature (klimaatscenarios)	Increase in enviromental temperature.	Steel	It's complicated. See corresponding explanation in thesis.	Low/Medium	
		Timber	Increased temperatures can be beneficial to timber structures due to a lower moist value increasing the strenght of the material. But increased temperature can also be detrimental due to wood-eating organism manifastation, plant growth, or brittle. Timber also expands with increased temperature.	Low/Medium	
		Concrete	Acceleration fo the Akali-Silica reaction. Potential increase in cracking ratio due to increased temperature.	Low	
Groundwater level alterations & subsidence (geodataframe from klimapedia)	Due to rain & evaporation. But also subsidence. Raise of seawater levels. The grounwater level can either raise or lower drastically. Draught leads to subsidence. The groundlevel decreases.	Steel	Settling and shifting of structure. Stress on the material.	High	Terzaghi's general bearing capacity (takes soil and water into account)
		Timber	Settling and shifting of structure. Stress on the material.	High	Terzaghi's general bearing capacity (takes soil and water into account)
		Concrete	Movement of the ground puts stress on the concrete causing it to crack. It can also tilt the entire structure exposing the reinforcement to unexpected movements. Acidic soil can also influence concrete.	High	Terzaghi's general bearing capacity (takes soil and water into account)
Flood (geodataframe from klimapedia)	Exposure to water and extreme loads. Caused by extreme percipitation and/or high sea levels.	Steel	Flooding causes three key issues: flood duration (material submerging), high velocity and flood-borne debris and degradation of the materials. Steel is good in withstanding the flood-borne debris. The main issues rise with the submering with water leading to corrosion.	Low/Medium	Flood impact calculation
		Timber	Weak to impact load. But also prone to become swollen and distorted due to exposure to moist.	High	Flood impact calculation
		Concrete	Prolonged submersion causes reinforcing steel to rust. But the concrete is also influenced due to its porous characteristics. Freezing of the water can cause even further harm.	Low/Medium	Flood impact calculation
Downburst & Wind gusts	Strong downdraft wind load caused by storms. "These winds can easily cause damage similar to that of a EF0 (65-85mph winds) or even EF1 (86-110mph winds) tornado, and are sometimes misinterpreted as tornadoes. " (National Weather Service) -> 65-85 mph = 104-136	Steel	Can help in changes of athmospheric moisture, which can increase corrosion.	Low	Wind load calculations
		Timber	Proven to be problematic due to improper engineering in context of high wind loads. Timber is also a common material in hurricane-frequent areas, proving that extreme wind loads can be catastrophic.	Medium	Wind load calculations

	km/h. 86-110 mph = 138-177 km/h. Strong wind load caused by storms. Maximum wind speed in Netherlands measured this year (2022): 114 km/h	Concrete	Wind gusts can bend and flex concrete structures, leading to cracking. Vibrations can also cause fatigue and cracking over time.	Low	Wind load calculations
Hail	Solid form of precipitation that can dent, shingle and glutter or crack.	Steel	Nothing impactful happens.		
		Timber	Hail can damage timber exposed to it, especially regarding the thin layers of external systems. The most common damage is on timber roofs caused by strong winds and hail. It has been reported that hail impact has resulted in poor performance of roof coverings.	Low/Medium	
		Concrete	Potential chippinh and cracking.	Low	
Thunder	Direct strike can cause a fire, chain failure of connected elements and shock wave damage. Can reach up to 30 000 °C.	Steel	Nothing impactful happens.		
		Timber	The heat of lightning can cause the burning of timber. Research has been done on evidence of timber structures hit by thunderstorms in many previous centuries. Timber with a higher humidity content cracked more quickly, with more significant damage and damage area. On the other hand, dry and low-density timber was easier to burn. Thick timber was more difficult to be damaged by thunder.	High	
		Concrete	Rapid expansion that leads to cracking.	Medium	
Storm/Heavy rainfall (geodataframe from klimapedia)	Exposure to a lot of water with possible low pH levels or acid rain (acid rain isn't occuring in the Netherlands anymore).	Steel	Increases corrosion rates.	High	Steel corrosion can be calculated
		Timber	The moisture content of timber determines its structural performance of it. Since climate change results in moist-related consequences such as a higher temperature, more rainfall and higher moist levels, it severely influences the potential of timber structures when exposed to it. Heavy rainfall can cause water to be absorbed by the timber, eventually leading to damage from swelling, shrinkage, cracking, and deformation.	High	Equilibrium Moisture Content Formula
		Concrete	Short-term heavy rainfall can reduce concrete's Compressive strength, splitting tensile strength, and shear strength by 50, 70, and 37%. The decline of the concrete microstructure is caused by the increase of the water-binder ratio of concrete, and the short-term heavy rainfall influences that.	High	Model for the evolution of concrete deterioration due to reinforcement corrosion?

HOW CAN THE RESILIENCE OF BUILDINGS CONCERNING CLIMATE CHANGE IN THE NETHERLANDS BE ASSESSED?

This chapter will develop an assessment method for both flood impact and temperature changes. This will be done based on previous studies where each material is exposed to the event has been analytically analyzed.

FLOOD IMPACT ASSESSMENT

Assumptions

For the initial development of the tool, the following assumptions have been made:

- The current tool will be developed for a 3 meter-high structure
- The structure will be one floor (Currently, no higher floors will be considered)
- The load in IFC specifies the number of columns on the ground floor, but only 1 column will be evaluated for the initial working tool.
- The script will be developed for two different connections: Fixed End Beam. PL at Any Point & Simple Beam with PL at Any Point.
- The impact of buckling is left out for now

Once the evaluation of one column is set, assessing all columns or specific columns is a matter of slight further development of the code (In this case, a for loop through all the necessary columns).

Calculations

Similar studies

Upon investigating to find quantified assessment methods for flood impact, several studies have been analyzed where flood damage is measured and calculated. Although these studies focused on cavity masonry walls or dikes in the Netherlands, the determination of the impact value of the flood remains the same: primarily hydrostatic, hydrodynamic, and breaking waves have been taken into account. From this, it can be apparent that these loads should play a role in assessing flood impact in the tool (van Haren, 2021) (Jansen, 2019) (Chen, 2016).

Since the studies mainly focused on predicting through calculation and then verifying through simulations (either scaled-down models in practice or digital simulations), the used formulas didn't seem to encapsulate a proper assessment in the researched tool for this thesis and seemed more theoretical than practical.

Thus, upon further research, the decision has been made to opt for a building code's method of assessing flood damage. Because building code calculations ensure that even without a simulation to compare afterwards, the practical aspects have been taken mostly into account (Gilbert Gedeon, 2011) (FEMA, 2011).

For this, the coastal construction manual of FEMA (Federal Emergency Management Agency) has been consulted.

The coastal construction manual (Determining the loads)

The manual covers hydrodynamic and hydrostatic forces, which coincide, and breaking waves. Another essential aspect that considers urban context, debris impact loads, is also part of the manual. Since urban context is relevant to this thesis, this seemed like a valuable addition and thus has been included. Specifically searching for formulas to quantify these three events, the following relevant information has been derived from the manual for the tool:

Hydrostatic load

The pressure that a static liquid, in this case, water, exerts on a surface is known as a hydrostatic force. Calculating the hydrostatic force per unit width from flooding against a vertical part uses the equation f_sta = 1/2 * gamma * ds2. Three variables are needed in the formula: gamma, which represents the specific water weight in kilograms per cubic meter; ds, which represents the design still water flood depth in meters; and f_sta, which means the hydrostatic force per unit width in kilograms per square meter. The hydrostatic pressure rises immediately in proportion to the specific weight of the water and grows with the square of flood depth according to the formula.

Hydrostatic Force Calculation

$$f_{sta} = \frac{1}{2} \cdot \gamma \cdot ds^2$$

f_{sta} = hydrostatic force per unit width (kg/m) resulting from flooding against vertical element
γ = specific weight of water (64.0*16.0185 lb/ft^3 to kg/m^3)
ds = design stillwater flood depth in meters

Figure 11 Hydrostatic Force Formula

Hydrodynamic

The hydrodynamic force equation, F_dyn = 1/2 * Cd * rho * V2 * A, describes the force applied to a column from a moving liquid, such as water. This equation considers several factors, including Cd, the object's drag coefficient; rho, the fluid's density; V, the fluid's velocity; and A, the object's frontal area. According to the equation, the hydrodynamic force acting on the object is proportional to the square of the fluid's velocity and the item's frontal area. The drag coefficient represents the column's ability to move through the fluid efficiently and differs per shape (square versus round column).

Hydrodynamic Force Formula

$$F_{dyn} = \frac{1}{2} \cdot C_d \cdot \rho \cdot V^2 \cdot A$$

F_{dyn} = hydrodynamic force (kg)
C_d = drag coefficient (2.0 for square piles and 1.2 for round piles)
ρ = density of water (kg/m^3)
V = velocity of water (m/s)
A = width * design water depth (m^2)

Figure 12 Hydrodynamic Force Formula

Breaking wave'

Structures can be exposed to significant forces from breaking waves, which can cause damage or failure of components. Understanding the physics and the loads occurring from breaking waves is crucial for designing structures that can withstand this event. The formula to calculate this force is F_brkp = 1/2 * C_db * gamma * D * H_b^2, where F_brkp represents the breaking in kg, C_db is the breaking wave drag coefficient, gamma is the specific weight of water, D is the pile diameter, and Hb is the breaking wave height which can be derived from the design still water depth.

Braking Wave Load Formula

$$F_{brkp} = \frac{1}{2} C_{db} \cdot \gamma \cdot D \cdot H_b^2$$

F_{brkp} = breaking force in kg
C_{db} = breaking wave drag coefficient (2.25 for square, 1.75 for round)
γ = specific weight of water (64.0*16.0185 lb/ft^3 to kg/m^3)
D = pile diameter in meters
H_b = breaking wave height in meters (0.78 * ds)

Figure 13 Breaking Wave Load Formula

Debris impact

An object's force during a collision or contact is called the impact force. Expressed in kilograms (kg), it is determined by dividing the object's weight times the velocity of water by gravitational constant and the impact duration in seconds. The formula to calculate this force is F_i = w * V / g * t where F_i represents the impact force in kg, w is the weight of the object in kilograms, v is the velocity of water, g the gravitational constant and the t is the duration of the impact in seconds.

Impact Force Formula

$$F_i = \frac{w \cdot V}{g \cdot t}$$

F_i = impact force in kg
w = weight of object in kg
V = velocity of water in m/s
g = gravitational constant in m/s^2
t = duration of impact in seconds

Figure 14 Impact Force Formula

The type of object that collides differs per urban setting. In a city, the chances that a car crashes with the structure are higher than when a building is set in plains. To account for the type of object that a structure is exposed to in an impact scenario, the following settings and values are used while using the Debris Impact calculation:

Type of urban setting	Type of object	Weight of object (kg)
City	Car	1500
Village	Small tree	655
Plains	Bushes/Wood debris	454

Regarding the impact duration, since little reference material exists according to the manual, the city of Honolulu's building code is consulted. The building code makes a difference between the used material for the structure. The building code is similar to mathematical models from dynamic theory; an explanation of this theory was beyond the scope of the manual but is also beyond the scope of this thesis. Regardless, the following values are used based on the building code:

Material	Impact duration
Concrete	0.1
Wood	1
Steel	0.5

Material properties

The tool will be developed for 3 types of materials: concrete, steel and wood. These 3 types of materials have their respective moment of inertia and elasticity modulus. The following values and formulas are used:

Material	Elasticity Modulus
Concrete	30 000 MPA
Wood	11 000 MPA
Steel	210 000 MPA

The MPA can differ based on the concrete, wood and steel type. Currently the tool will not take this into account, but this can easily be added to the code in the future as it is a matter of an addition.

Material	Second moment of inertia
Concrete	Inertia = (((WidthMM * (HeightMM**3))) / 12)
Wood	Inertia = (((WidthMM * (HeightMM**3))) / 12)
Steel	Excel lookup table

Due to the different shapes of steel columns, the moment of inertia will be derived from an Excel table. The current code is only for square columns. With a small adjustment this can be expanded to round columns as well.

Working with the loads

The calculated loads in the previous chapter need to be released on a column and determined whether the structure can withstand it. Initially, the proper way to calculate columns subjected to perpendicular loads is through the finite elements model. But due to the complexity and size of the topic of developing an open-source finite elements model tool, it can be concluded that it is out of the scope of the thesis and timeframe. Hand calculations from StructX are used as a replacement, and the column has been treated as a beam. These calculations will later be compared to simulations in Karamba 3D to check whether it is a feasible way to determine whether a column can withstand these loads or not. See Image below for the visual representation of the load, image from the Coastal Construction Manual.

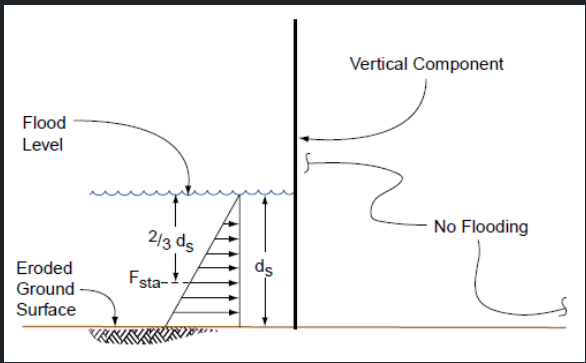


Figure 15 Figure from Costal Construction Manual showcasing the load context during a flood

Upon consulting one of the researchers (& teacher) in the Faculty of Civil Engineering and Geosciences at the TU Delft, it was concluded that this load case can be translated into a fixed end beam with simple support on the other side. The fixed side representing the connection of the column to the foundation. Since not every column-foundation is fixed, the alternative for a hinge connection will also be considered.
Making the load cases as follows (Formulas from StructX):

For the one side hinge other side is simply supported:

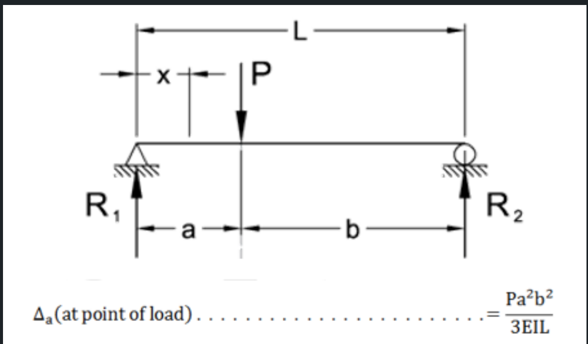


Figure 16 Fixed on both ends load case from StructX

For the one side fixed and the other side simply supported:

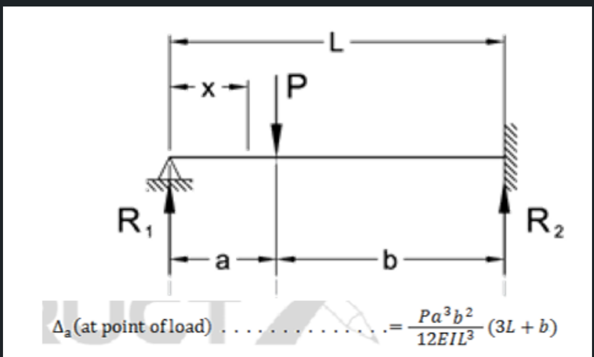


Figure 17 Fixed on one end and hinge on the other load case from StructX

Maximum allowed deflection

According to the International Residential Code for One- and Two-Family Dwellings, the following vertical deflections limits are given (Weyerhaeuser Company, 2018):

STRUCTURAL MEMBER	ALLOWABLE DEFLECTION
Rafters having slopes greater than 3:12 with no finished ceiling attached to rafters	L/180
Interior walls and partitions	H/180
Floors and plastered ceilings	L/360
All other structural members	L/240
Exterior walls with plaster or stucco finish	H/360
Exterior walls-wind loads[a] with brittle finishes	H/240
Exterior walls-wind loads[a] with flexible finishes	L/120[d]
Lintels supporting masonry veneer walls[e]	L/600

Figure 19 Table from Weyerhaeuser Company with allowable deflections based on International Residential code for One- and Two-Family dwellings

L/240 is the value that will be used to determine the maximum allowed deflection for the columns in the beam calculation.

This specific building code was chosen because it applies to small structures. The current tool focuses on a 1 story structure.

Determining the damage

In order to determine the amount of damage that would occur to a variable structure with variable material, python packages and software was consulted. Upon further investigation, it was clear that there was either no freely accessible data for the Netherlands, or the sources which did have these kinds of data were behind a paywall. The best option amongst all of the investigated (see table below), is Climada and FEMA Hazus. But unfortunately, FEMA Hazus is behind a paywall and Climada is behind a big learning-curve (Meant for climate scientists) and lack of data (open source for material behaviour but also flood intensities in the necessary format).

Package	Type	Comment
Climada	Python	Open-source. Climada graphs of damage do not allow reading of the values x and y. Climate sets need to be developed to assess properly. On a very professional level for climate scientists. Provides default flood damage graph, but the values aren't retrieveable due to the limitation of the function creating the graph (even though it's plotted through matlabplot).
FEMA Hazus	Arcgis + Hazus	Behind a paywall due to Arcgis requirement (But students can get a license), not open source.
Delft-FIAT	Python (?)	Claims to be open-source but nothing can be found, also not on the open-source page of Deltares that was referred to in the presentation pdf.
Damagescanner	Python	Open-source. Specifically developped by Dutch people in regards to the context of the Netherlands. Unfortunately no datasets for flood damage, the package contains data on land usage which was used for a paper that assessed flood damage. Very early in development (v0.6), example code doesn't run.
Fathom Flood Hazard	API, data & maps	In depth data & maps, but behind a paywall(?). Definitely not open source.

Figure 18 Table describing findings on considered different packages for the hazard assessment

Because of this, an alternative had to be sought to be able to still somehow determine the amount of damage that structures obtain in respect to the flood depth. Unfortunately, this couldn't be categorized into materials, but a paper has established an empirical formula for the determination of flood damage in respect to flood depth based on cases in Italy. The paper also compares existing models from literature or trained. According to the paper the following root function is the best suited (Mattia Amadio, 2019):

$$y = 0.13\sqrt{x}$$

y = Relative Damage (factor)

x = Water depth (m)

Figure 20 Relative damage prediction through water depth

The following graph shows the relationship of the relative damage with the flood depth of the root function:

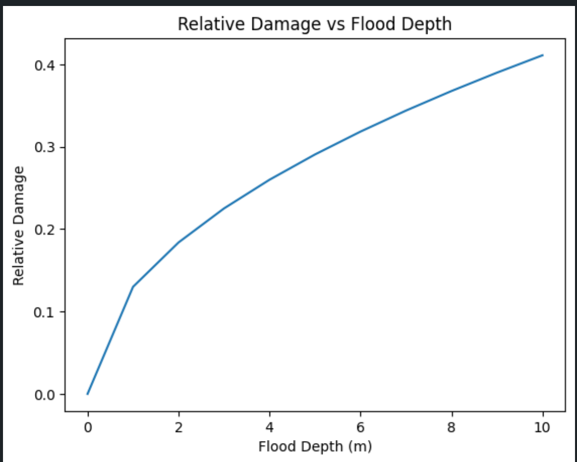


Figure 21 Graoh showing relationship between flood depth and the relative damage

Due to the timeframe of this thesis, this relative damage prediction will be used in the flood damage calculation.

Recovery & Repairs

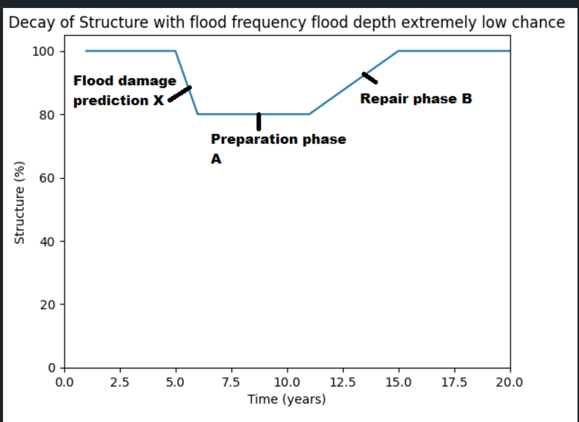


Figure 22 Line graph containing 3 different portions: flood damage, preparation phase and repair phase

Prediction X (As can be seen in the figure above) is described in the previous chapters.

After the damage occurs, preparations and recovery & repairs occur. To determine the timeframe before repair starts (Phase A), the REDi Rating System is used (Ibrahim Almufti, 2013). The rating system used is initially for earthquake design. Still, since both earthquakes and floods are environmental disasters and orthogonal loads on the structure, the values from recovery from an earthquake are assumed to be similar to that of a flood. Unfortunately, REDi flooding is not out yet, so the earthquake version is the best option for now. In the future, when the flooding version is out, the values can be updated.

For the recovery & repairing phase (Phase B), the Performance Assessment Calculation tool called PACT of FEMA will be used (FEMA). This tool has fragility and consequences data that describes losses and repair costs with times for different materials.

Preparation Phase

Before the repairing phase starts, there is a recovery phase. The following assumptions and choices have been made for this thesis's situation:

For a structure, the number of workers for repairing is supposedly 1 according to the guidelines for REDi for this thesis's case.

The REDi graphs indicate of times with a probability of the time not being exceeded. To be conservative in the used values and minimalize potential values that exceed, the probability of not exceeding 90% of the cases is used.
Long-lead time components (components that require processing and aren't readily available) will not be assumed for this thesis since Steel, wood, and concrete is readily available. Potential delays are also ignored since the values are already conservative.

This recovery phase is as follows according to the REDi rating system:

- The first step is a post-earthquake, at this moment flood, inspection. This inspection takes 10 days (probability of 90%) for non-essential facilities.
- Secondly, the design phase and the engineering mobilization take place; in this period, minor to major damage downtime times are described, the

values are respectively 10 weeks/20 weeks/75 weeks (Repair class 1/Repair class 2/Repair class 3) with a probability of 90%. The repair classes are described in the table below.

- After this, the time required to secure funds occurs. In the Netherlands, flood damage is always covered (According to the Consumers Association). For this reason, the value of obtaining funds from insurance is assumed. This is 25 weeks with a probability of 90%.
- After financing, a contractor needs to be found. This takes longer than usual due to the post-catastrophic event situation. For non-essential facilities under 20 stories, this value lies at 15 weeks for Repair class 1 and 39 weeks for repair class 2 and above.
- Obtaining permits is the next step. For this, 3 weeks is assumed for Repair class 1 and 12 weeks for Repair class 3. Since no value is given for repair class 2, this value will be assumed to be exactly between 1 and 2: (12+3)/2 = 7.5 weeks.
- After all the preparations, the repair time is obtained from a PACT analysis. In the next subchapter, this will be done for each material.

Repair Class	Repair Description
3	Heavily damaged *structural* or *non-structural* components which pose a risk to 'life-safety' and must be repaired to achieve **Re-occupancy**. Consequently, these components must also be repaired to achieve Functional Recovery and Full Recovery, since by definition they follow Re-occupancy.
2	Damaged *non-structural* components which do not pose a 'life-safety' risk or otherwise hinder Re-occupancy but must be repaired to achieve **Functional Recovery**. Consequently, the component must all be repaired to achieve Full Recovery, since by definition it follows Functional Recovery.
1	Minimal or minor cosmetic damage to *structural* or *non-structural* components which do not hinder Re-occupancy or Functional Recovery but must be repaired to achieve **Full Recovery**.

Figure 23 Repair Classes according to REDi Rating System (ARUP)

Recovery & Repairing phase

The following repair days can be extracted from the PACT database for timber, steel and concrete columns. Each repair time is based on 4 columns (assumed structure in previous chapters):

Material	State	Repair time (Days)
Steel (B1031.011a)	Initiation of crack	15 to 25
	Brittle/Crack	22 to 31
	Complete fracture of the column	25 to 36
Concrete (B1041.001b)	Residual crack, but no fractures or buckling of reinforcement	15 to 23
	Residual cracks and exposure of transverse reinforcement and joints.	23 to 35
	Cracks in beam or joints, longitudinal reinforcement exposed, crushing of core concrete may occur. Reinforcement replacement may be required.	28 to 43
Wood (B1071.041)	Minor cracking	1 to 4
	Moderate cracking or crushing (in corners)	3 to 9
	Significant cracking and crushing, buckling and tearing of tracks	9 to 30

Figure 24 Table with values from PACT FEMA

For the tool development, the highest values will be assumed. Based on the deformation the state will be linked.

The amount of repair days corresponding to the state will be determined based on how much the maximum deflection exceeds in the flood calculations.

For the linking of the damage classes to an amount of deflection, values from HAZUS is used. For exceeding 1 to 1.67 times the deflection limit, slight damage will be considered, corresponding to repair class 1. Whereas past 1.67 times the max deflection till 2.7 times the max deflection a moderate damage will be assumed, which means repair class 2. Lastly, past 2.7 times the max deflection and further will be seen as damage class 3, which means heavy damage.

Damage State	HAZUS Descriptor	Post earthquake Utility of Structures	Evidence	Outage time	Expected Ductility Fa
1	None	No damage	None (pre-yield)	-	0.33
2	Slight	Slight damage	Cracking	< 3 days	1.0
3	Moderate	Repairable damage	Large cracks cover spalled	< 3 weeks	1.67
4	Heavy	Irreparable damage	Failure of components	< 3 months	2.0
5	Complete	Irreparable damage	Partial/total Collapse	> 3 months	2.7

Figure 25 Definition of damage states (HAZUS)

TEMPERATURE IMPACT ASSESSMENT

Assumptions

For the initial development of the temperature assessment the following assumptions were made:

- The outside temperature is also the temperature that the structure is exposed to (no cooling or heating considered). The tools' purpose is to show the difference in degradation due to the increase in temperature, not give a direct case specific indication because taking all the contextual aspects (passive, cooling, Rc value etc.) would be too much for the scope of the thesis. The case-specific indication can only be done when real life predictions data are available, but the tool can be extended to this.

- For timber, for now, the type of wood used is pine wood. For further development, the activation energy needs to be adjusted accordingly to the type of wood if this data is available. This type of wood also needs to be extracted out of the IFC model manually and/or user input.

Calculations

Arrhenius equation

As mentioned in the previous chapter on the materials regarding corrosion being a problem for steel, the Arrhenius equation plays a role in the calculation and hereby the assessment of it.

Arrhenius Equation

$$k = A \cdot e^{-\frac{E_a}{RT}}$$

k = Rate constant

A = Pre-exponential factor

E_a = Activation energy

R = Gas constant

T = Temperature (in Kelvin)

Figure 26 Formula of Arrhenius Equation

The Arrhenius equation is a formula that uses the temperature and activation energy of a determined reaction and calculates what the rate of this reaction occurring is in light of the variable temperature. This way, the influence of temperature on the corrosion rate of steel can easily be calculated. The equation is expressed as k = Ae^(-Ea/RT), where k is the rate constant, A is the frequency factor, Ea is the activation energy, R is the gas constant, and T is the absolute temperature. Below you can see the dependance of temperature to the rate constant.

The preexponential factor and the activation energy is determined by the used material and process/situation. The gas constant is a fixed value of 8.31446261815324 J K-1 mol-1. The temperature here will be the variable based on current and predicted climate data.

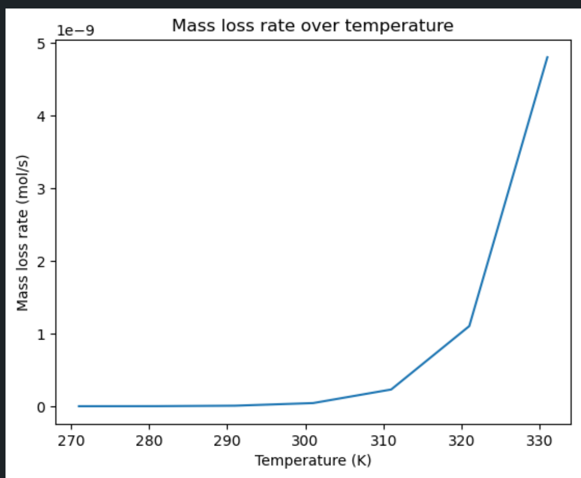


Figure 27 Mass loss rate versus temperature graph based on the Arrhenius Equation (Sample activation energy taken)

After obtaining the rate constant for the particular reaction scenario, this can be converted into a weight loss per seconds through unit conversions.

The first step is dividing the rate (molecules) to moles by dividing the value with the avogadro's number. This is 6.022e23.

Afterwards, the amount of moles can be converted into a weight through a simple multiplication with the molar mass of the material.

Steel

For steel corrosion, the Arrhenius equation will be used. The activation energy used is 32.47 * 1000 (J mol-1). For the preexponential factor 3.713 * 10^25 is used. This value is based on research on mild steel in acidic environment. The same research also used the Arrhenius equation to determine the corrosion rate (Hashim, 2020).

For the molar mass of steel, 55.845 gram/mole is used (Mercer, 2017). This is based on Iron Fe, this is because steel is predominantly made out of iron. Around 90% of the weight of steel is from iron.

Wood

For wood, the Arrhenius equation will also be used, because the Arrhenius equation is also used in wood degradation but also on determining timber damage when set on fire. The activation energy and preexponential factor is from research that is modeling the pyrolysis of biomass. Pyrolysis is the thermal decomposition of materials in elevated temperatures. The value used is 165.0 * 1000 (J mol-1). The preexponential factor used is 1.57* (10^12). Both values are for Pine wood (Soria, 2016).

For the molar mass of pine wood, since wood is mostly cellulose and with taking calcium caught up in the wood into account, C6H12O6 + Ca is used. The molar mass results fromhis 220.2339 gram/mole (plantchicago, 2018).

Corrosion of concrete

The corrosion of concrete's steel is a bit more complex due to the layer that is over the steel. Different formulas derived from the Arrhenius equation have been proposed by numerous research. One paper gathered a decent amount of those formulas, and compared them, eventually ending up advising a new formula for the corrosion of reinforced concrete structures (Shi, 2023).

The following formula is proposed with all relevant substitutions already applied:

$$i_{corr}(t) = 1.38\frac{(1-w/c)^{-1.64}}{\sqrt[3]{(1+t)\,C}}\exp\left[1.23 + 0.618\ln C_t - \frac{3034}{T(2.5+RH)} - 5\times10^{-3}\rho\right]$$

Figure 28 Formula from the used report (Shi, 2023)

With w/c being the water/cement ratio, t being time duration, C is the concrete cover thickness in mm, Ct is the chloride content by weigfht of concrete in kg/m3, T is the ambient temperature in Kelvin, RH is the relative humidity and rho is the concrete resistivity in kΩ cm.

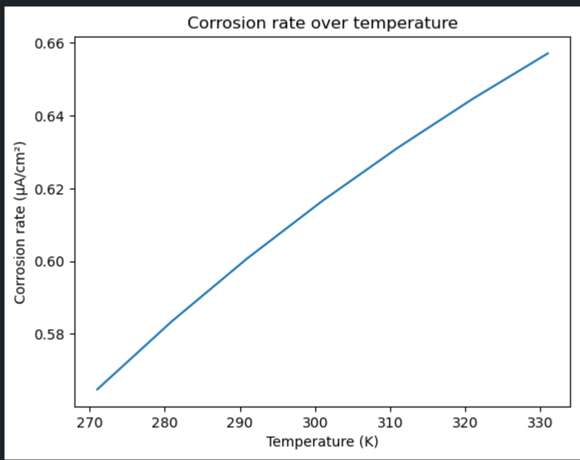


Figure 29 Graph of the formula weighing corrosion rate over temperature

The temperature in Kelvin and the relative humidity are relevant for the assessment. Thus, these values need to be obtained for the evaluation tool somehow.

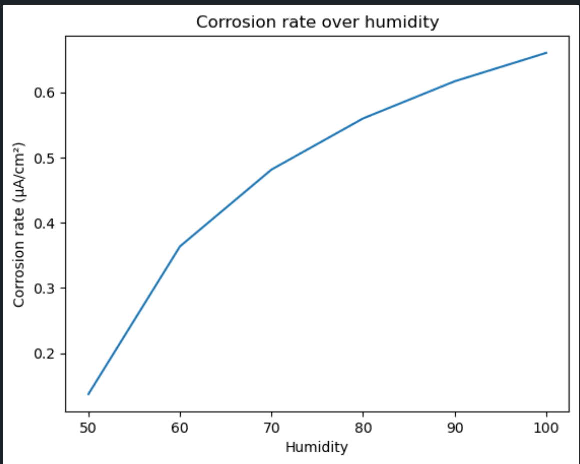


Figure 30 Graph of the used formula weighing corrosion rate over humidity

In this case the t will be year. The current formula also considers that the corrosion will be less throughout the years due to a firm protective layer forming when the steel corrodes, but also the amount that can corrode decreasing. For this reason, the formula should be run for each year to get the correct outcome for each duration/time.

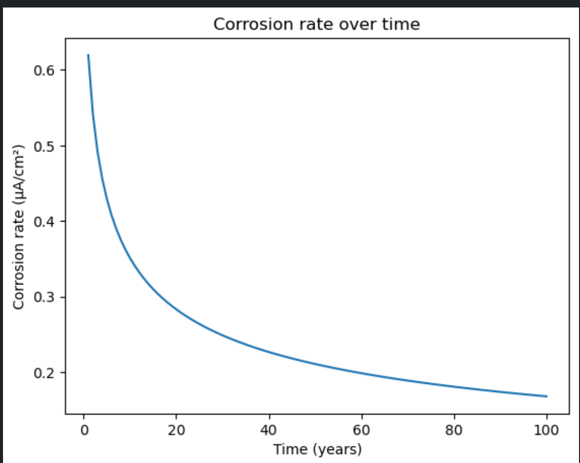


Figure 31 Graph of the used formula corrosion rate over time

The formula returns the icor(t) in µA/cm2 per t. The Faradays constant will be used to convert the µA/cm2 per year into workable units. In a published journal, the corrosion mass loss, for steel in this case, was also determined by the faradays constant (Shuxian Hong, 2020).

The faradays constant allows for the conversion of µA/cm2 to g/cm2 per year. The faradays Law is as follows:

$$m = \frac{xM}{vN_A} = \frac{QM}{eN_A v} = \frac{QM}{vF}$$

Figure 32 Faradays Law formula (Wikipedia)

By substitution of the faradays law, the following convertion formula can be used (ASTM Standard):

CR = I_{corr} K EW / d A

CR	The corrosion rate. Its units are given by the choice of K
I_{corr}	The corrosion current in amperes.
K	A constant that defines the units for the corrosion rate.
EW	The equivalent weight in grams/equivalent
d	Density in grams/cm³
A	Area of the sample in cm²

By using 3272 for the K constant, the outcome is mm/year.

Mass loss to performance loss

After finding the mass loss, the amount of column lost is defined. Based on this, a ratio can be found, for example (extreme example) 20% loss of the column in 20 years, which leaves 80% of the column standing. This would result in a cross-section loss of, if we assume the loss is equal on all sides of the column, the cube root of the ratio (Because 3 times the cube root of the ratio equals the ratio). See the image below.

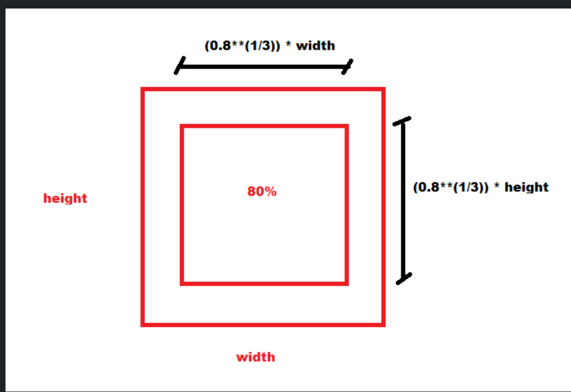


Figure 33 Visualization of the cross-section with ratio loss

After finding the new height and width based on losses on all sides, the new inertia for the material can be calculated. Based on this new inertia, the new deflection values can be determined with the same flood loads calculated in year 0 for the flood assessment. This way, the influences of temperature on the degradation and the impact of the degradation on the structural performance can be calculated. This also shows that the flood calculation’s result is influenced by time due to other climate-related aspects.

For a column made out of wood with a fixed connection, 200mm x 200mm x 3000 mm in dimensions and in a 5000 mm flood scenario (for significant load values), the following old and new deflection values can be calculated:

Old deflection: 56.81 mm

New deflection: 76.5 mm

Difference: 19.69 mm

For a mass loss of 5% in the same scenario, this difference would be 4 mm.

WHAT METHODS CAN BE USED TO NUMERICALLY ASSESS THE RESILIENCE OF BUILDINGS IN THE NETHERLANDS TO FLOOD DAMAGE AND TEMPERATURE INFLUENCES?

The impact of a flood on a structure can be assessed by simulating the flooding damages with deflection calculations according to the coastal construction manual from FEMA. The outcomes for each material, wood, concrete and steel, are different due to the difference in Elasticity modulus.

The damage assessment can be done through reference cases, in this case through a formula defined based on data from Italy, and the recovery and repair period can be determined by FEMA and Hazus databases. The duration of the recovery phase can be determined based on the REDi rating system. All the respective formulas and values can be input for the tool’s script.

When it comes to the influence of temperature, an empirical concrete corrosion formula can determine the mass loss, and the degradation of wood and steel can be calculated through the Arrhenius equation. For concrete, a specific formula is used for corrosion because the concrete layer needs to be considered. After getting the corrosion ratios or the material degradation ratio, they can be converted into mm/year through the faraday’s equation.

After determining the mass loss, the new cross-section size can be predicted, and this value can be used to calculate the structural influence of the mass loss. In this thesis, re-doing the deflection calculation was chosen because this reflects back to the flood calculation, concluding that the flood calculation is year bound because the increase in degradation from temperature increase directly influences the deflection amount.

ASSESSMENT WITH PYTHON

The previous chapter has determined the assessment method; this chapter will proceed with the suggested assessment method and start translating it into a script in python. The method of how this is done and what relevant information was needed, and how it was obtained is described in this chapter.

IFC

For this thesis, IFC is chosen to be the file type. The significance and power of IFC lies within the fact that it is the universal communication method between every kind of party in the construction sector. IFC isn't tied to particular software and allows designers and companies to use their preferred methods, making it a universally preferred and easy method of sharing models.

Apart from that, the biggest strength of IFC, is that IFC is the method of communicating information and values in regard to components in a building; every measurement and type of a component is described within an IFC, making it easily accessible for anyone who needs to obtain information on specific components of a building.

Translating into a script

The model

The Python package ifcopenshell can be used to read IFC models.

Regarding the IFC models used for the development of the code. The following open-source IFC files were used:

- Schependomlaan
- Medical Dental Clinic
- Esplanades, Estonia

These models are published by the Open BIM Standards on Github. The repository can be found under BuildingSMART Sample test files. They can be found on GitHub.
For the assessment of the temperature and flood resilience, the following characteristics of the structure are relevant (Since we are assessing columns only the component IfcColumn is relevant):

- Height and Width of the column
- The material of the structure
- Length of the column
- (For steel) Thickness
- (Optional) Number of columns on the ground floor

Other relevant information is location & type of connection. These variables will be obtained using the frontend tool, and not derived from the IFC, for user-friendliness and the freedom to change the location to see what influence this will have on the outcome.

Python Script Results

Setup

Initially the idea was to extract the height, width and length information from the parameters of the columns. Unfortunately, this wasn't an effective method because the information management within the model differed based on language and in which software the model was modeled (example: Revit IFC models had a different parameter naming than ArchiCAD). Because of this, an alternative had to be sought.

The alternative was directly assessing the geometry of the column instead of the data. The script is relatively simple because openifcshell already has an example code on how to work with geometries. With the example code, all columns' vertices is extracted. The vertices are grouped together lists. The lists are built based on x, y, z coordinates in the respective order. Taking the z values and finding the difference between those 2 values gives the column lenght.

The same is done for the height and width but based on the x coordinates. This method works because the geometries are all treated individually position-wise and not in an angle.
In terms of finding the material type, this is always in the name of the geometry. For this a simple python if statement is used, for example: "if "steel" in list name", then material = "steel" is used.

Findings

- Dictionaries have different keys and parameter titles/names based on the modeler's preference, the software it is in (Archicad vs. Revit), etc. Due to the differences in how the data Is stored in dictionaries (relevant parameters were under different key values), all needed extraction of data methods need to be in an independent way of how the key in a dictionary is named
- Due to the reason above extracting dimensions from the parameters of an IFC element proved difficult. For this reason, the dimensions need to be extracted from the geometry or shape.
- A solution to the dictionary problem is to directly assess the shape/geometry of the columns and read the height out of that.
- Further research would benefit the automation of the values. While working with different models and ifcopenshell, it was found that the mpa could also be extracted to have a more accurate calculation.
- Currently the example script provided with this thesis only selects one pre-defined column and does not run it through all columns. A method of finding how to determine whether the column connection is a hinge or fixed would also be a great addition.

FLOOD EVALUATION

Translating into a script

Determining the amount of flooding (Urban Data)

Klimaateffectatlas offers data regarding flooding. Flood amount and chance maps are specifically developed to inform the user how much risk a location is exposed to and how deep it might be. This data is valuable input for determining the loads to which a particular structure will be exposed in its given location.

Klimaateffectatlas also has an API that allows the data to be loaded instead of downloaded. Given how big datasets such as these might become and how the downloaded version will have to be updated manually in case changes occur, the API is the preferred method for the tool.

The map "overstromingsdiepte" is used. This map offers 4 different scenarios and gives a flood depth for each scenario in meters:

- High chance: 1 in 10 year occurring flooding
- Middle chance: 1 in 100 year occurring flooding
- Small chance: 1 in 1000 year occurring flooding
- Very slim chance: 1 in 100000 year occurring flooding

The first two chance scenarios are the most important regarding the lifespan of a building.

The model

Through the Python package ifcopenshell the IFC is read, and the relevant data is extracted: type of material, the column's dimensions (height, width, and span) and whether it is on the ground flood or not (here it is assumed that a flood will not hit the columns on the first floor and above). The user input is needed for the type of connection of the column. This is because not all IFC models are detailed enough.

After obtaining the relevant details, the flood assessment as described in the previous chapter will be run. Following that, a deflection check will be done whether it is exceeded or not if it does a damage class and amount of damage will be tied to the amount of deflection and based on this the recovery and repair days will be determined. The results of the amount of damage on the structure and the repair and recovery will be combined into a graph from matlabplot. See figure below for the flowchart of the script.

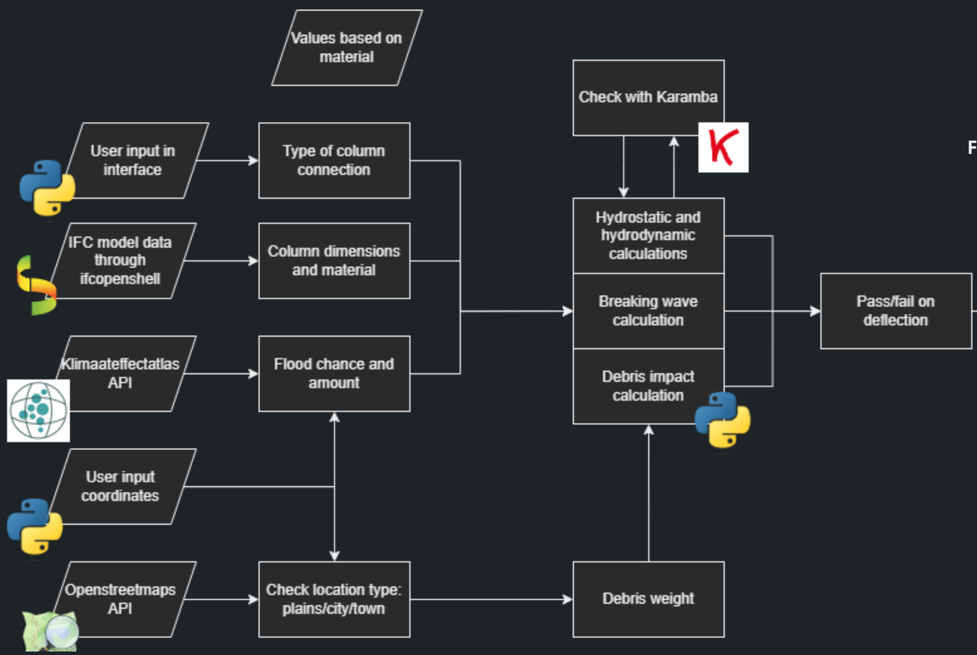


Figure 34 Flowchart of flood assessment

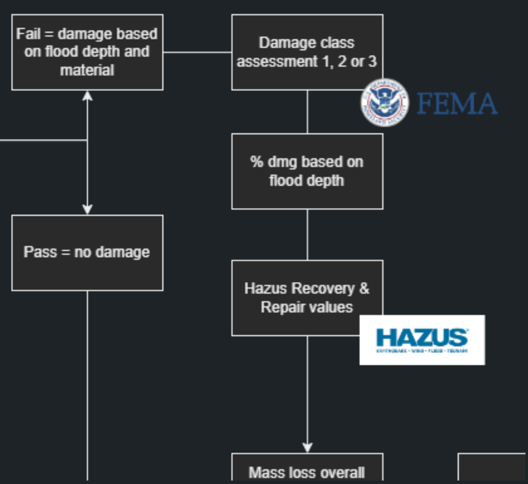


Figure 35 Flowchart Flood Assessment

Verifying/Checking the hand calculations

The current conditions are used:

design_stillwater_depths = [3, 3, 3, 3] (The location does not matter here because the Stillwater_depth is fixed for the sake of this check)
connection = "fixed"
material = "concrete", "steel", "wood"
Length = 3 # m
Height = 0.2 # m
Width = 0.2 # m
Thickness = 0.07 # m (only for steel)
WaterType = "salt"

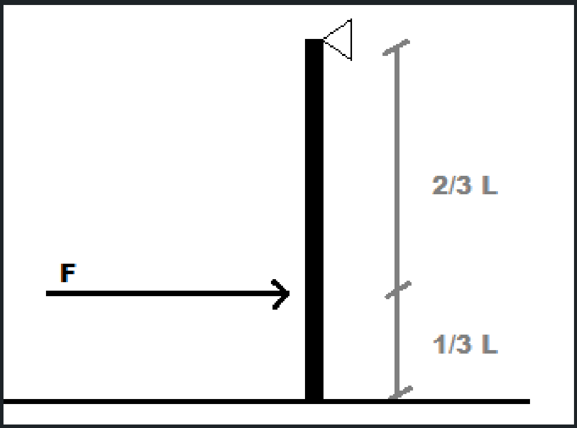


Figure 36 Sketch of setup in Karamba3D

	Specifications (in meters)							
Number	Material	Elasticity MPA	Height	Width	Flood Depth	Connection type	Thickness	Length
1	Steel	210000	0.2	0.2	3	Fixed	0.07	3
2	Wood	11000	0.2	0.2	3	Fixed	NA	3
3	Concrete	30000	0.2	0.2	3	Fixed	NA	3

Script result						
	Breaking wave		HS + HD		Debris impact	
#	Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)
1	6.21	0.20	11.71	0.37	16.27	0.52
2	6.21	1.05	11.71	1.97	8.14	1.4
3	6.21	0.38	11.71	0.72	81.37	5.02

Karamba result						
	Breaking wave		HS + HD		Debris impact	
#	Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)
1	6.21	0.18	11.71	0.34	16.27	0.47
2	6.21	0.78	11.71	1.47	8.14	1.02
3	6.21	0.23	11.71	0.43	81.37	3.00

Figure 37 Script results Karamba3D

The materials used for this calculation can be seen in figure below.

The steel results are very close to each other, mainly because Karamba has steel properties int egrated within the package. Karamba is a tad more complicated for concrete because reinforced concrete isn't easily taken into account, the library for wood isn't extended as well. For this, the WIP version of Karamba from GitHub Was downloaded and used (Clemens-Preisinger, 2022).

Even though concrete and wood may not have a result as accurate as steel, it technically does not matter because the hand calculations' only difference in input is the Shear modulus. So the fact that steel works appropriately means that the hand calculations are accurate. The only possible side note would be that materials besides steel are less predictable with hand calculations. But the main reason this check failed on the wood and concrete end is most likely due to possible faulty input in Karamba or the lack of options for accurately calculating these materials in Karamba. Regardless, the values in Karamba are lower than the hand calculations, which is expected because the hand calculations are more conservative due to a lack of input. Because of the amount of difference between the Karamba3D calculations and the hand calculations, a warning that the deflection amounts being on the conservative side should be mentioned in the tool.

The Karamba script specifically for steel can be seen in the next page. The entire script and an image version of the entire script with the different materials can be found in the GitHub repository of this report.

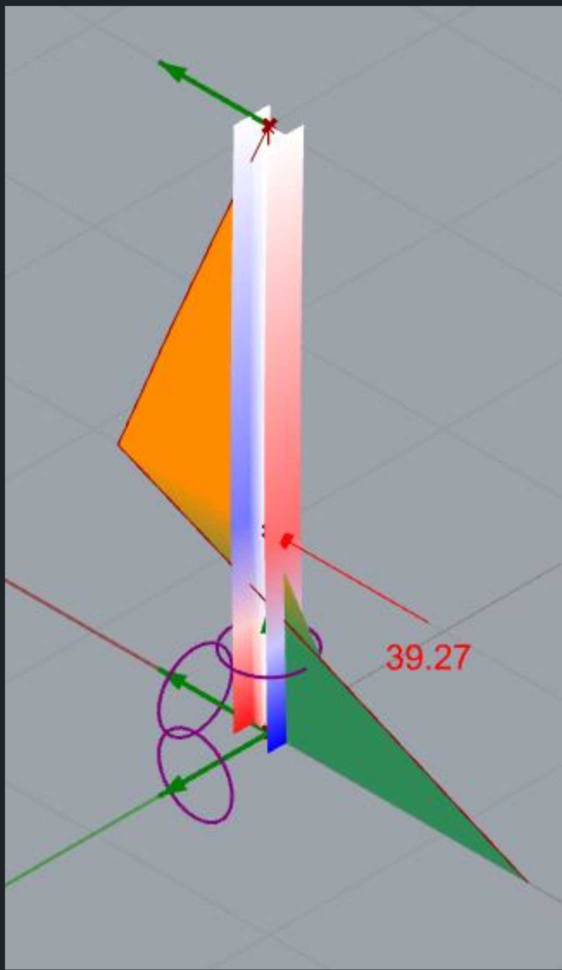


Figure 39 Screenshot from Karamba setup

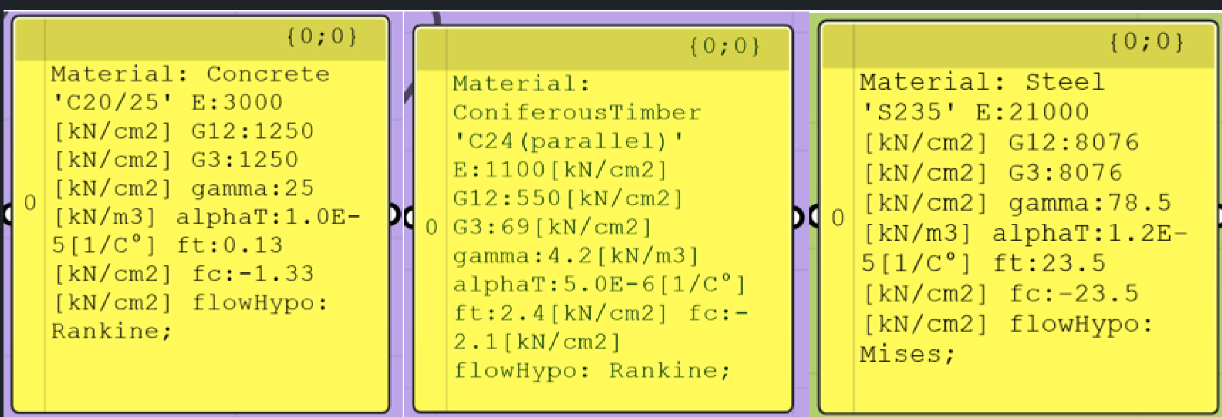
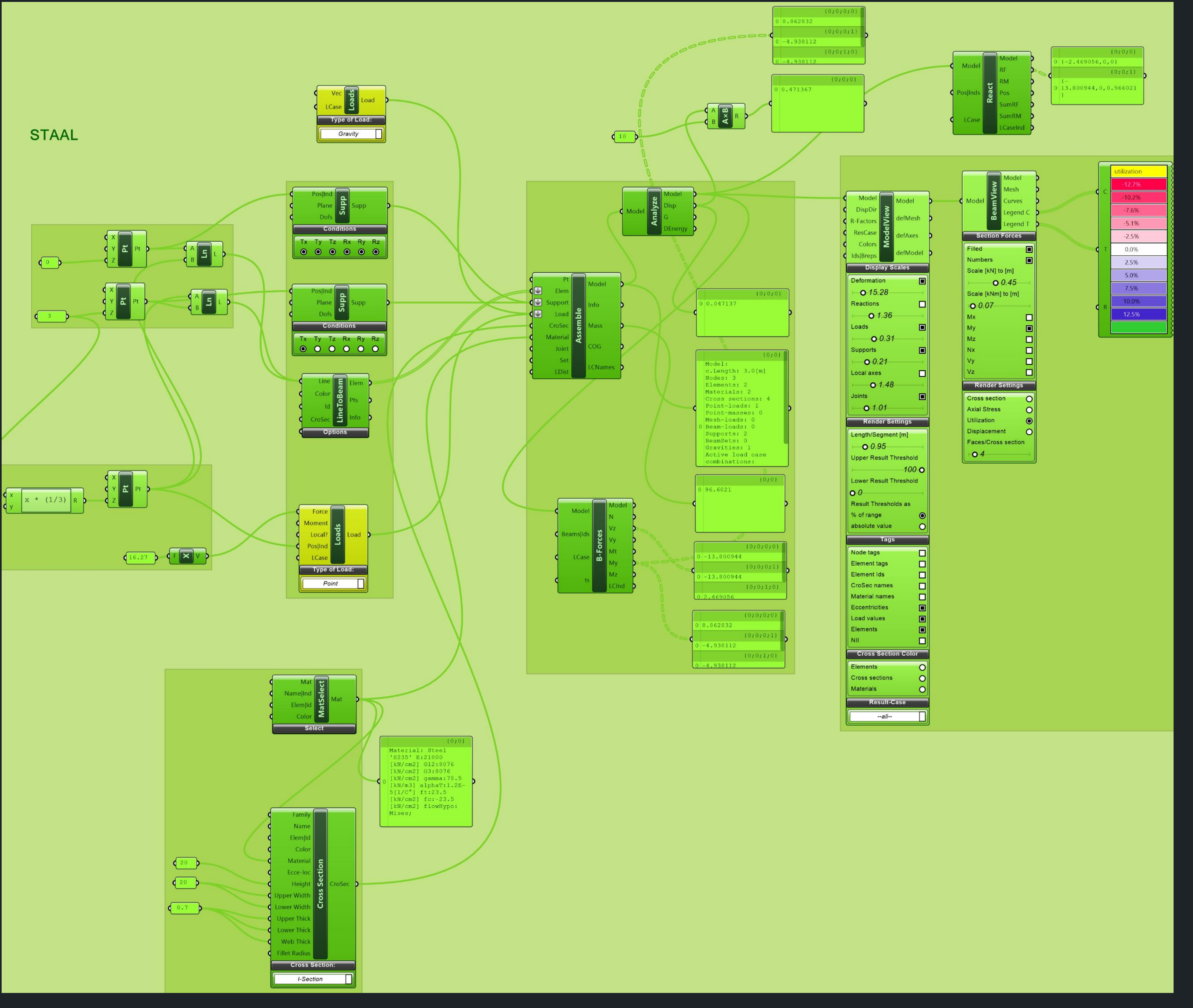


Figure 38 Screenshots from used materials in Karamba3D

Karamba 3D Script



Python Script Results

Setup

Based on the findings in the previous chapter and the further implementation of it, a work-flow/flowchart has been developed and this script has been written.

The developed python script will be run over different locations and flood depths in order to test the assessment before integrating it in the tool.

The following cases were chosen:

- Delft, TU Delft Bouwkunde (Low risk zone) – Wooden Structure
- A random plain in Gorinchem – Concrete structure (Middle risk zone) See Figure 41 A random plains in Gorinchem (Goole Maps)
- Landgoed de Brouwketel in Angeren Wooden Structure (High risk zone) See Figure 42 Landgoed de Brouwketel Angeren (Google Maps)
- Fictional location flood depth 30, 20, 10, 10 – Wooden structure
- Fictional location flood depth 30, 20, 10, 10 – Steel structure
- Fictional location flood depth 30, 20, 10, 10 – Concrete structure

See Appendix A for the result graphs for each case.

Figure 40 TU Delft Bouwkunde (Google Maps)

Figure 41 A random plains in Gorinchem (Goole Maps)

Figure 42 Landgoed de Brouwketel Angeren (Google Maps)

Table with results

Location	**Lon/Lat**	**Type of location (API outcome)**	**Material + Structure size (m) + connection type**	**Flood depths (Very low, low, middle, high chance in meters)**	**Forces (kN)** **(Very low, low, middle, high chance)**	**Deflections exceeded for 4 cases?** **1= yes 0 = no**	**Damage factor (0.22 = 22% loss) (Very low, low, middle, high chance)**

Location 1: Delft, TU Delft Bouwkunde (Low risk zone) – Wooden Structure - hinge	y = 52.005750
	x = 4.370344
		city of Delft	connection = "hinge"
			material = "wood"
			Length = 3 # m
			Height = 0.1 # m
			Width = 0.1 # m
				0 0 0 0	overstromingsdiepte_extreem_kleine_kans
					This location has no determined risk for flooding by Klimapedia
					overstromingsdiepte_kleine_kans
					This location has no determined risk for flooding by Klimapedia
					overstromingsdiepte_middelgrote_kans
					This location has no determined risk for flooding by Klimapedia
					overstromingsdiepte_grote_kans
					This location has no determined risk for flooding by Klimapedia
						0, 0, 0, 0	0, 0, 0, 0

Location 2: Random Plain in Gorinchem (See Error! Reference source not found. **Gorinchem) - hinge**	y = 51.855422 x = 4.967723	city of Gorinchem	connection = "hinge" material = "concrete" Length = 3 Height = 0.1 Width = 0.1	2.9375, 2.9375, 1.626, 0	overstromingsdiepte_extreem_kleine_kans For Design Stillwater Depth: 2.9375 breaking 2.975733694778963 kN hydrodynamic + hydrostatic 4.990860760975399 kN Debris 80.52202726583577 kN overstromingsdiepte_kleine_kans For Design Stillwater Depth: 2.9375 breaking 2.975733694778963 kN hydrodynamic + hydrostatic 4.990860760975399 kN Debris 80.52202726583577 kN overstromingsdiepte_middelgrote_kans For Design Stillwater Depth: 1.6265000104904175 breaking 0.9123184397195703 kN hydrodynamic + hydrostatic 1.69119645021365 kN Debris 59.91737768089467 kN overstromingsdiepte_grote_kans This location has no determined risk for flooding by Klimapedia	1, 1, 0, 0	0.22280877451303394, 0.22280877451303394, 0, 0
Location 3: Landgoed de Brouwketel in Angeren Wooden Structure (High risk zone) - hinge	y = 51.920175 x = 5.969967	plains	connection = "hinge" material = "wood" Length = 3 Height = 0.1 Width = 0.1	3.960925817489624, 3.696451425552368, 3.232856273651123, 2.099125862121582	For Design Stillwater Depth: 3.960925817489624 breaking 5.41042934035227 kN hydrodynamic + hydrostatic 8.768099150404712 kN Debris 2.8300148272889585 kN overstromingsdiepte_kleine_kans For Design Stillwater Depth: 3.696451425552368 breaking 4.712032955533459 kN hydrodynamic + hydrostatic 7.691048429169645 kN Debris 2.7339014689095835 kN overstromingsdiepte_middelgrote_kans For Design Stillwater Depth: 3.232856273651123 breaking 3.6042184574828227 kN hydrodynamic + hydrostatic 5.972822047734835 kN Debris 2.5567222747681795 kN overstromingsdiepte_grote_kans For Design Stillwater Depth: 2.099125862121582 breaking 1.5195509652595331 kN hydrodynamic + hydrostatic 2.681502485674528 kN Debris 2.060201012278433 kN	1, 1, 1, 0	0.2587269725320007, 0.24994005099590386, 0.23374188975171734, 0

Location	Lon/Lat	Type of location (API outcome)	Material + Structure size (m) + connection type	Flood depths (Very low, low, middle, high chance in meters)	Forces (kN) (Very low, low, middle, high chance)	Deflections exceeded for 4 cases? 1= yes 0 = no	Damage factor (0.22 = 22% loss) (Very low, low, middle, high chance)
Case 1: Fictional location flood depth 5, 4, 3, 2 – Wooden structure fixed	NA	City	connection = "fixed" material = "wood" Length = 3 Height = 0.1 Width = 0.1	5, 4, 3, 2	overstromingsdiepte_extreem_kleine_kans For Design Stillwater Depth: 5 breaking 8.621410433040001 kN hydrodynamic + hydrostatic 13.680751151341104 kN Debris 10.505355776935875 kN overstromingsdiepte_kleine_kans For Design Stillwater Depth: 4 breaking 5.5177026771456 kN hydrodynamic + hydrostatic 8.933189913072884 kN Debris 9.396275858019495 kN overstromingsdiepte_middelgrote_kans For Design Stillwater Depth: 3 breaking 3.103707755894401 kN hydrodynamic + hydrostatic 5.191334178804663 kN Debris 8.137413594011306 kN overstromingsdiepte_grote_kans For Design Stillwater Depth: 2 breaking 1.3794256692864 kN hydrodynamic + hydrostatic 2.455183948536442 kN Debris 6.644170377105031 kN	1,1,1,0	0.2906888370749727, 0.26, 0.22516660498395405, 0
Case 2: Fictional location flood depth 30, 20, 10, 10 – Steel structure fixed	NA	City	connection = "fixed" material = "steel" Length = 3 Height = 0.1 Width = 0.1 Thickness = 0.07	5, 4, 3, 2	overstromingsdiepte_extreem_kleine_kans For Design Stillwater Depth: 5 breaking 8.621410433040001 kN hydrodynamic + hydrostatic 13.680751151341104 kN Debris 21.01071155387175 kN overstromingsdiepte_kleine_kans For Design Stillwater Depth: 4 breaking 5.5177026771456 kN hydrodynamic + hydrostatic 8.933189913072884 kN Debris 18.79255171603899 kN overstromingsdiepte_middelgrote_kans For Design Stillwater Depth: 3 breaking 3.103707755894401 kN hydrodynamic + hydrostatic 5.191334178804663 kN Debris 16.274827188022613 kN overstromingsdiepte_grote_kans For Design Stillwater Depth: 2 breaking 1.3794256692864 kN hydrodynamic + hydrostatic 2.455183948536442 kN Debris 13.288340754210061 kN	0,0,0,0	0,0,0,0
Case 3: Fictional location flood depth 30, 20, 10, 10 – Concrete structure fixed	NA	City	connection = "fixed" material = "concrete" Length = 3 Height = 0.1 Width = 0.1	5, 4, 3, 2	flood depth extremely low chance For Design Stillwater Depth: 5 breaking 8.621410433040001 kN hydrodynamic + hydrostatic 13.680751151341104 kN Debris 105.05355776935876 kN flood depth low chance For Design Stillwater Depth: 4 breaking 5.5177026771456 kN hydrodynamic + hydrostatic 8.933189913072884 kN Debris 93.96275858019493 kN flood depth middle chance For Design Stillwater Depth: 3 breaking 3.103707755894401 kN hydrodynamic + hydrostatic 5.191334178804663 kN Debris 81.37413594011306 kN flood depth high chance For Design Stillwater Depth: 2 breaking 1.3794256692864 kN hydrodynamic + hydrostatic 2.455183948536442 kN Debris 66.4417037710503 kN Deflection: Column is OK permitted amount is 12.5 mm occuring amount is 0.1734 mm	1,1,1,0	0.2906888370749727, 0.26, 0.22516660498395405, 0

Findings

- The random plain is considered a city by the API, whereas it can be seen from the location picture that it is a plain and not a city setting. It is nearby the city, though, but not close enough to be considered a case where debris loads of the city should be applied.

- Locations like Delft are not at risk of flooding, so whatever material is chosen does not matter regarding flood resilience.

- The location in Gorichem is outside the city, so it could be a desired location due to the housing crisis in the Netherlands. But the flood chances on the site show that it is essential to consider these values.

- Steel is a flood-resilient material compared to wood and concrete. This is especially true in dire circumstances with flood levels exceeding 3 meters. So, in the high-risk zones for flood or locations with a flood, the amount flooded will be higher than 3 meters. Concrete and wood is a risky options unless over-dimensioning of the structure is the case. This tool can quickly check whether it is worth opting for a thicker column.

- The used max deformation for all materials in this case is 12.5 mm, because all cases had the length of 3m. This is a very forgiving deflection amount, especially for thin structures and columns. For this reason, when this deformation is exceeded 100% of the predicted damage is reduced from the structure health percentage.

- Not rounding up numbers is relevant but not the most appropriate way to present it. Proper rounding ups need to happen visually when showing these values in the tool.

TEMPERATURE EVALUATION

Translating into a script

The model

To compare the current and future situations regarding climate change, both this kind of climate data needs to be obtained. Figure below shows the workflow of the script.

Climate data

Since the climate data is relevant for being able to calculate with the Arrhenius equation and the corrosion formula for concrete, these values need to be obtained for the given location (by the user). In order to do so an API will be needed. The following API's have been considered while searching for the most suitable one for this thesis:

Open-meteo turned out to be the best option because it provides historical data, current data, and future predictions. Openmeteo also does not limit access regarding API calls, but they do ask for a fair use (not more than 10 000 unless contacting).

Package	Type	Comment
KNMI	API	Requires API key
knmy	Python package	KNMI data. Limited to 2 weather stations but no API key required.
Open-meteo	***API***	***Completely free and open-source, historical data provided, climate prediction data provided for different countries.***
open-weather-map	API	1000 API calls for free. Historical API paid. Only 5 days forecast available and current weather.
visualcrossing	API	1000 API calls a day for free, provides history data, 15 days forecast and more. No climate prediction models included.

Figure 43 Table with used packages and their respective comments

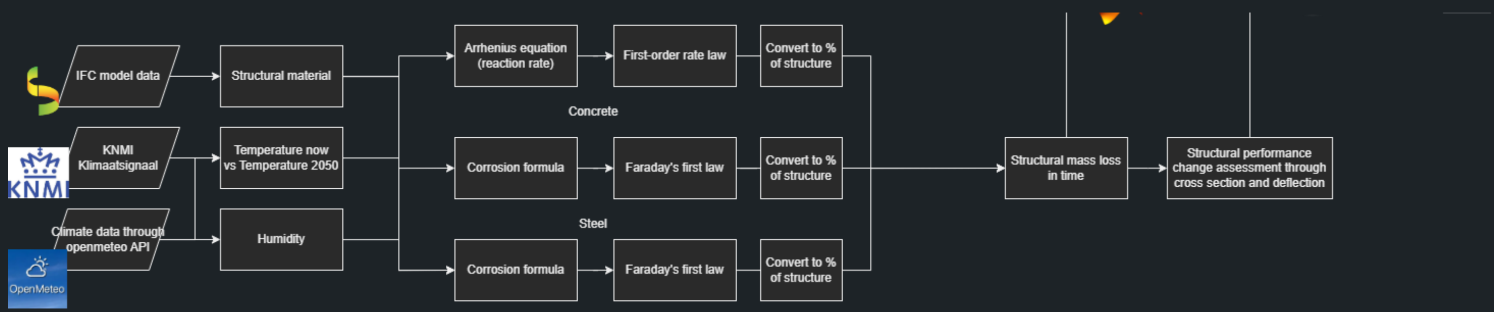


Figure 44 Flowchart section of Temperature script

Climate predictions

All used values will be based on predictions for the year 2050.

Through open-meteo, data from the past year's entire year will be requested, and the maximum temperature of that year and the average humidity will be used. The predicted temperature increase, and humidity decrease of KNMI will be added to this value. For temperature, this is 2.3 Celsius, whereas, for the average humidity, this is a subtraction of 2.5%. This way, the new value will be the predicted value from KNMI.

These are the values that will be used for the temperature assessment.

On the other hand, climate data predictions from Germany Max Planck Institute for Meteorology, Hamburg 20146, Germany will be real-time requested through the API for the given location by the user. The tool will show these values to the user to compare values between the KNMI predictions. But also, to get a general idea of the occurring changes for the given location. These values aren't directly meant to serve as a comparison, indication and possible confirmation to the predictions from KNMI.

Since the open-meteo API and Max Planck Institute offer predicted values for a lot of themes, the following values will be requested: max precipitation, max dewpoint, max relative humidity, max windspeed and max temperature. This will be done for both now and in 2050, both of this data will be shown to the tool user. Next to it the KNMI predictions will be shown.

Python Script Results

Setup

Through match statements for the material type and the geometry data likewise from the flood assessment, the formulas mentioned in the theoretical subquestion in the previous chapter will be implemented in the script.

Based on the current temperature and the predicted temperatures for 2050 a corrosion rate and rate of reaction will be calculated. This will give an old rate and a new rate; both can be plotted simultaneously.

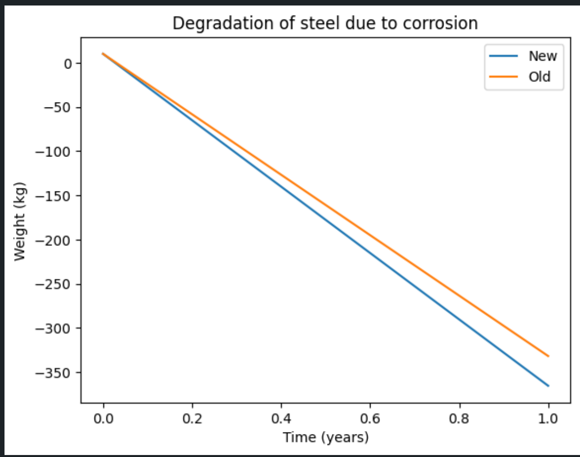


Figure 45 Representation of how degradation due to corrosion would look like

After calculating this, the new deflection can also be calculated.

CLIMATE RESILIENCE ASSESSMENT

Combining the outcomes

The % damage mass loss comes from the flood assessment, whereas the structural mass loss in time comes from the temperature assessment. Both these are translated into a graph that is combined. The combined graphs and precombined graphs are used in the tool's user interface and communicated to the designer. All the scripts necessary for this process are published on GitHub so it becomes open source. The development of the user interface will be done in the next chapter.

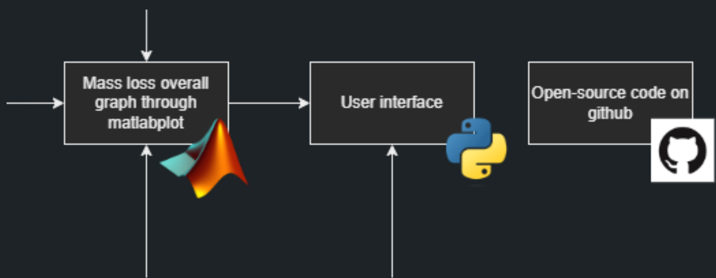


Figure 46 Portion of the overall flowchart where everything comes together

HOW CAN A CLIMATE RESILIENCE ASSESS-MENT METHODOLOGY BE EFFECTIVELY IMPLEMENTED INTO A SCRIPT USING PYTHON WITH OPEN-SOURCE PACKAGES?

Ifcopenshell is a great opensource package to work with IFC models. Even if the IFC model isn't properly modeled in terms of data exchange with regards to dimensions, ifcopenshell can cover that up by getting vertices out of the geometry.

Regarding information necessary for flooding, klimaateffectatlas offers an API to access the necessary data. Using hand calculations for the deflections caused by flood impacts proved to be feasible with a Karamba3D comparison.

The current script for flooding has some shortcomings regarding determining the type of environment, which is done through OpenStreetMap's, but it has proven to not always be accurate. Further investigation on how this could be done in a more accurate way is suggested. Apart from that, the flood script can be evolved further by expanding structural performance-related calculations instead of only deflections.

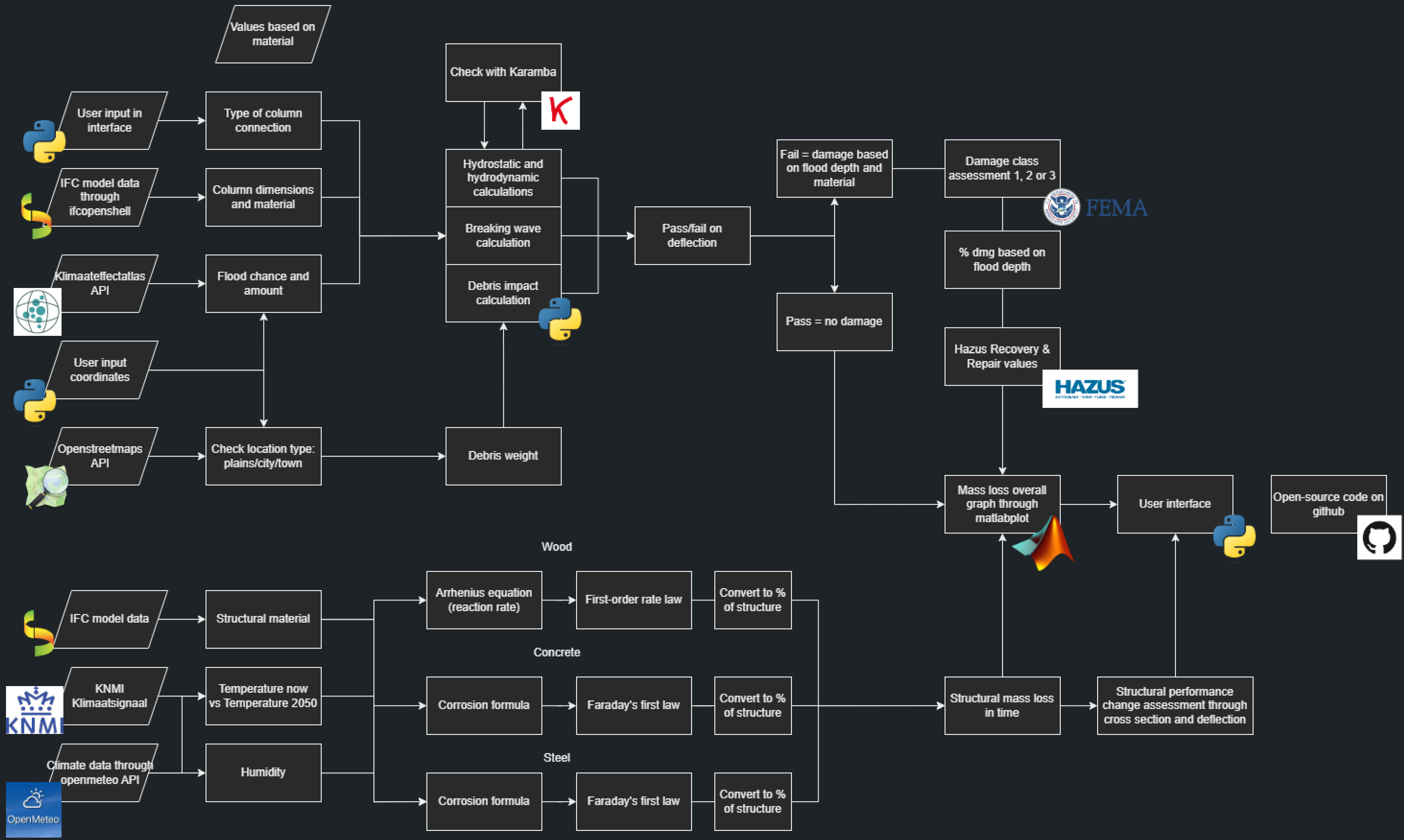
For temperature assessment, for the necessary information open-meteo data is used. Open-meteo is open-source and completely free, and also offers different future prediction data from climate change. This makes this API the perfect fit for the job.

After obtaining the necessary information, with the theory from the previous chapter a script can be developed for each material to determine the mass loss and plot both old and new in a graph. Lastly what the influence of that mass loss in on the deflection can be calculated.

The flood damage graph with the recovery and repair can be combined with the mass loss from the temperature calculations. This combined graph will be the final outcome of the tool.

In the next page the flowchart of the tool can be seen.

THE TOOL'S FLOWCHART (BACK END)



THE TOOL

DEVELOPMENT

Initial idea

For the tool, the following criteria are set:

- Open-Source
- In Python to correspond to the back-end, but also to prevent a higher learning curve on future contributors
- Easy to use with only necessary input
- A modern UI/UX design instead of Windows XP-like
- The tool & relevant scripts will all be uploaded on Github to make it open-source
- The user needs to be able to input location and other necessary things

Possible methods

Packages

The following packages for GUI development in Python are considered:

Package	Comment
Tkinter	Offers all possible functionalities that Tkinter can have. Yet lacks significantly in the design sense. It looks ancient compared to today's tools unless a lot of time is spent developing a good theme. Tkinter is a GUI (Graphical User Interface)
customtkinter	The pre-built theme for tkinter. Easy map input integration also offers a pretty modern UI/UX. Lacks of theme coloring require much effort/time to change. Also, has complications in implementing 3d models. But aside from that, the ideal option for a simple GUI.
Tkinter designer	Exports figma designs to Tkinter. Older than Proxlight Designer. Works only visually. A good option for developing small/not many action applications that require looking "pretty" with images.
Proxlight-Designer-v2	Export figma designs to Tkinter. Works only with images and positioning. Aside from that, it offers no extra functionality. No 3d model viewer whatsoever support. A good option for developing small/not many action applications that require looking "pretty" with images.
Matdeck (from Labdeck)	Solves the 3d viewer issue partially. A lot of freedom for designing. Unfortunately paid tool. It does offer a tutorial.
Mercury	Mercury is a package that translates jupyter notebooks into a tool. It offers less freedom than Tkinter in terms of design. But Mercury is the quickest and most efficient way to make a simple tool.
Kivy	Kivy needs to be installed, unlike Tkinter. But it is an open-source framework for developing interfaces. It offers possibilities for multi-touch and mobile apps, unlike Tkinter, which is mainly used for desktop apps. Kivy is a NUI (Natural User Interface). Kivy is smaller than Tkinter in examples and documentation. It is making Tkinter an easier option than Kivy.

Figure 47 Table with considered packages for the tool and comments

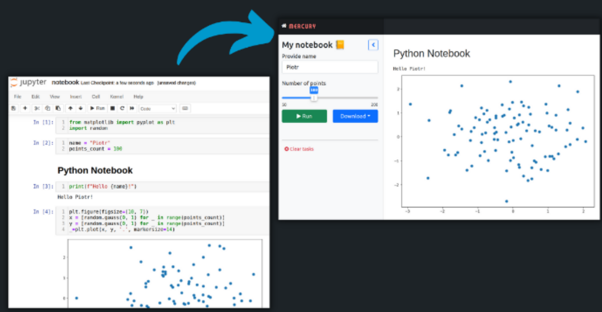


Figure 48 Mercury Package (Picture from their website)

Customtkinter turns out to be the most applicable given the criteria set for the tool. Customtkinter is also a free and open-source package.

Customtkinter is also perfect regarding the tool's modern look and input possibilities and comes with a map where you can select the location.

Problems

Tkinter brings a lot of complications in terms of 3D design. The initial proposal for the look of the tool can be seen in the figure below.

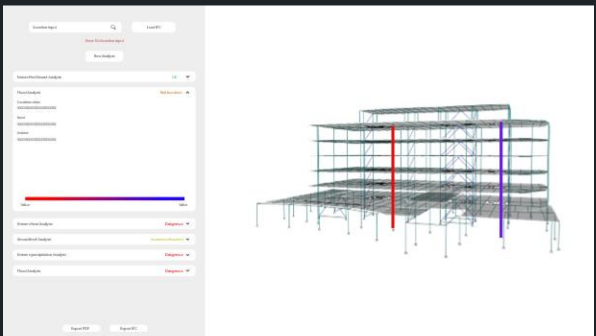


Figure 49 Initial Design Idea for the tool

An attempt was made to implement a 3D viewer in Tkinter for IFC models specifically. Unfortunately, an IFC viewer isn't necessarily supported. This resulted in forcefully converting the IFC files to obj files, but while doing so, the models weren't appropriately preserved. Because of this reason, the attempt to bring the 3D viewer was seized.

This 3D view will unfortunately not be viable to replicate in Tkinter with the given time and the knowledge required regarding Tkinter & Python visual coding. Because of this reason, the 3D view is scrapped as the assessment results can also be shown in a graph and table instead. For further development, implementing the 3D results view is the next step.

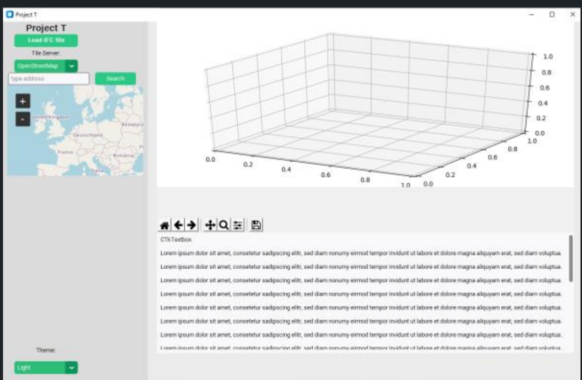


Figure 50 Screenshot of the progress of implementing 3D view

UI/UX progress

The theme, options, maps & Colors

Regarding the options, the tool can be switched from dark to light mode and the user interface can be zoomed in or zoomed out with the scaling function to suffice the tool for different screen resolutions. This function was already part of customtkinter, which makes this package a strong choice in terms of UI and UX.

The existing dark and light colors are locally altered to enhance the tool's look. Shades of purple were chosen based on reference searches of different kinds of dark modes. The purple dark mode tools looked the most modern.

The following map views that can be selected are implemented in the tool:

- OpenStreetMap
- Google Maps
- Google Satellite
- Stamen BW Map

The UI and UX will be discussed in the next subchapter. Two versions are made.

Version 1

Version 1 was designed with the idea that the tool should show every necessary data with one eye glimpse. Because only two events are assessed, this will fit.

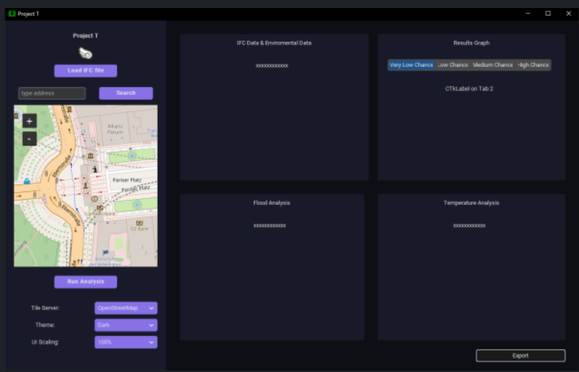


Figure 51 Screenshot of the tool, Dark mode

Different flood events, in this case, will be shown based on the selected chance of flooding (1 in 100, 1 in 1000, etc., as described in the corresponding chapter)

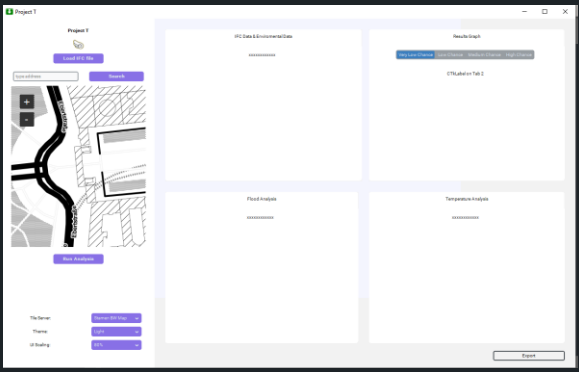


Figure 52 Screenshot of the tool, Light mode

The interface will have the results of flood, temperature, combined resilience graph, and general input information separately but also bundled together in a bigger frame. This way, the user can distinguish between these 4 clusters and have a proper overview of the input parameters while also looking at the results of each theme or their combination.

Version 2

Version 2 focused on a cleaner and less "full" interface where each theme and assessment has a different view page. This version is also made considering possible future expansions of the tool.

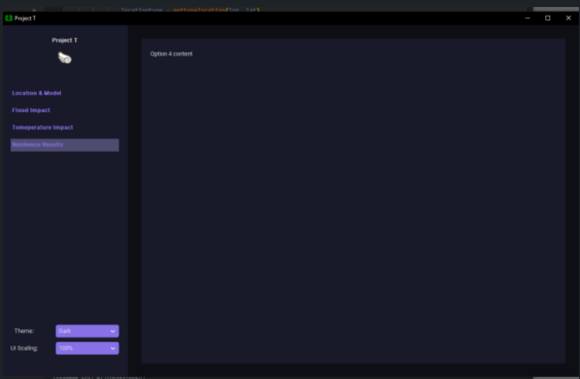


Figure 53 Screenshot of developed alternative UI for the tool

Unfortunately, this theme caused issues in coloring with the dark and light theme of customtkinter because custom theme colors were used.

A method to solve this is by making a theme file from scratch or editing an existing one. But these theme files are pretty big, and it would cost the necessary time that is better used to improve version 1 for the scope of this thesis. For further improvement, version 2 is the better option.

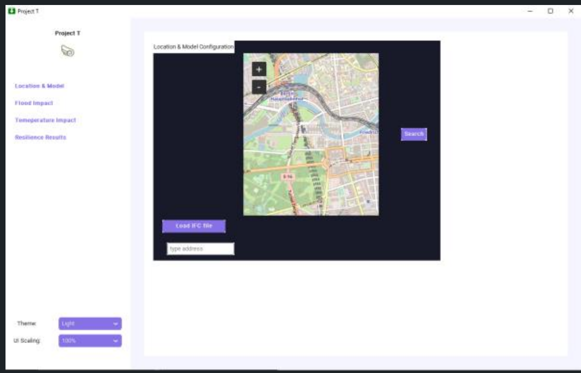


Figure 54 Screenshot of the light mode issue with the alternative UI

Logo

A logo is developed since the tool needs some sort of image/representation on what it does instead of leaving the app icon blank.

For the logo, the idea is to combine a graph (due to the results being resilience in a graph) and a shield (due to the shield representing resilience). Based on this principle, the following logo has been designed:

Figure 55 Designed logo for the tool

The chosen colors are based on colors that work well with dark and light modes in the tool. Initially, purple was blue because, in psychology, blue represents trust, and green represents sustainability and nature. But purple was still picked over blue because this would fit the tools' theme color better (London Image Institute, 2020).

Final idea

Version 1 is definitely the better option for now due to the complications in theme colors that occur with version 2 and the fact that only two assessments are currently run. Hence the need for an interface where more assessments can be run, and a bigger area is reserved for the results isn't needed. But when the tool's back-end is further developed into deeper assessments and different themes (more than flood and temperature), version 2 is definitely the version that should be used instead.

For the final version of the tool, the backend assessment (Flood assessment), load in IFC & Temperature assessment will be combined, and the script results will be projected through the interface. The following proposal

See the image below for an indication of how the tool should look. The real tool may vary depending on circumstances during development.

WHAT IS AN OPEN-SOURCE APPROACH FOR CREATING A FRONT-END TOOL IN PYTHON TO ASSESS IFC MODELS?

The chosen and most applicable way for the climate resilience tool is through Tkinter. This ensures that the front-end code is also in Python, just like the back-end (the assessments). In terms of the design and looks of the tool, a customtkinter package is used. Customtkinter provides an already partially set up User Interface (UI). For the tool's logo, a shield with a graph in it is chosen, because this represents the tool's functionality.

Through the usage tkinter in combination with customtkinter, the tool is useable by downloading the corresponding packages in the Python code. On the other hand, the back end is only made through openly available APIs (that don't require keys) and Python packages. This ensures that the entire tool is made of license-free software/packages. The source code of the tool, as well as the back-end assessment, are published on github. This ensures the tool is open-source.

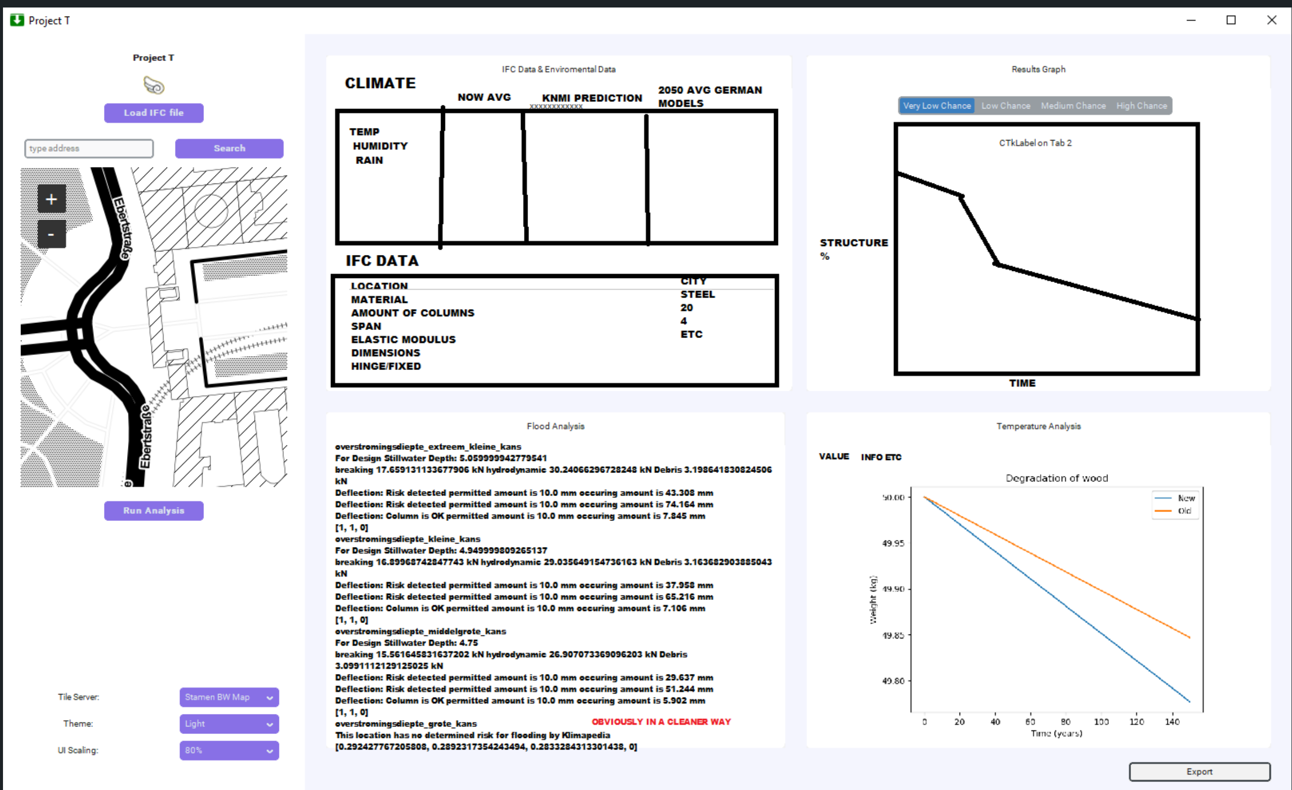
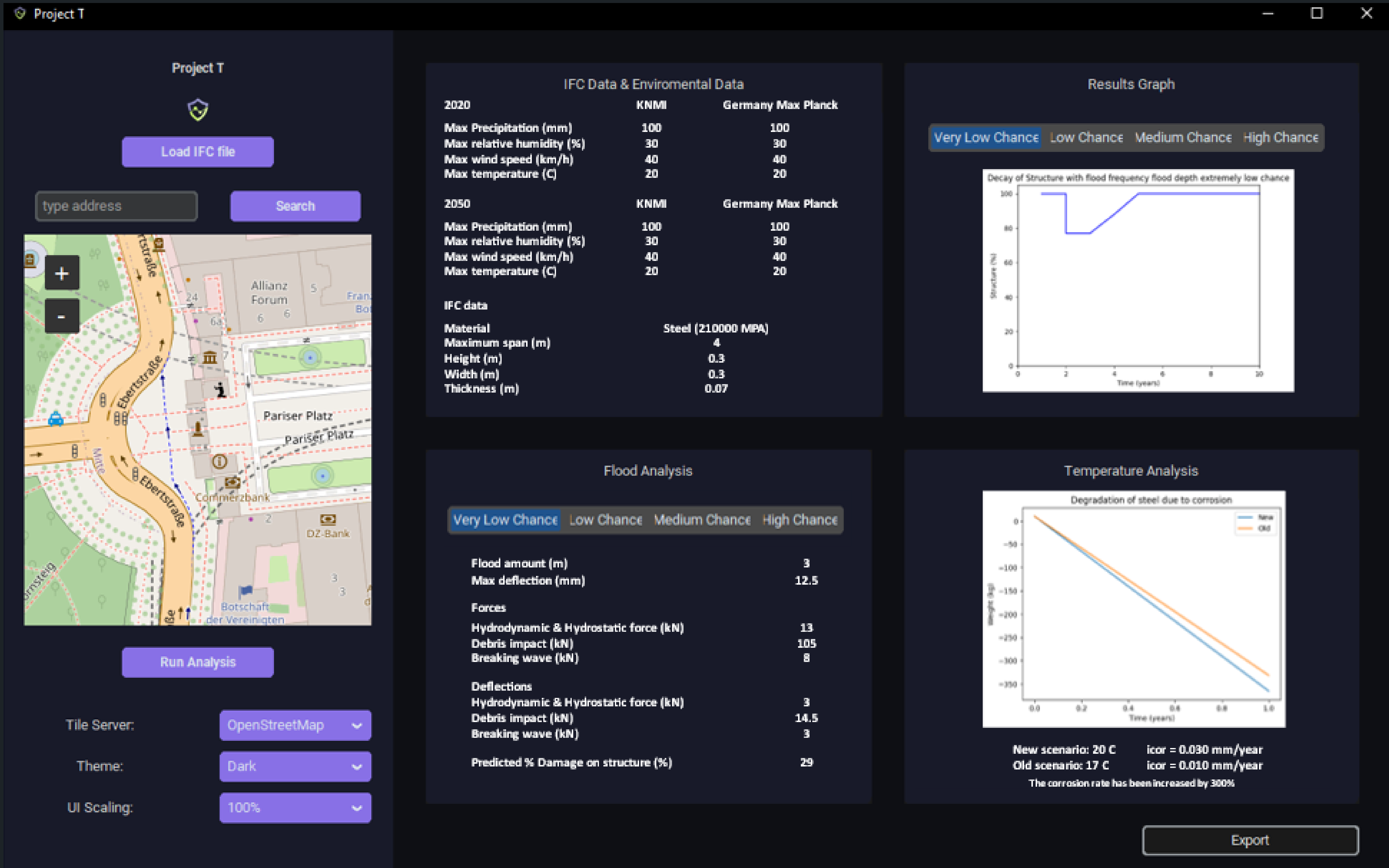


Figure 56 Suggested filling method of the tool with the backend

THE TOOL'S FINAL DESIGN (FRONT END)



CONCLUSION

HOW CAN WE ASSESS IFC MODELS REGARDING THEIR CLIMATE RESILIENCE CONCERNING CLIMATE CHANGE IN AN OPEN-SOURCE MANNER?

Climate change influences the climate in the Netherlands. The changes that are occurring according to KNMi are as follows:

- Temperature increase
- Condensation increases with higher dew points
- More solar radiation due to decrease of clouds
- Low pressure due to jet streams
- High humidity due to increase in temperature
- Wildfires due to lightning, sun, heat and human activities.
- Drought due to changed airstreams
- Subsidence due to drought
- Groundwater level alterations due to rain, evaporation, and subsidence
- Increased chance of flooding. Caused by extreme precipitation and/or high sea levels.
- Downbursts, thunder & wind gusts due to high jet stream behavior
- Hail due to heavy rainfall from increase in condensation. temperature and high humidity.

All these events have an either direct or indirect influence on building materials. Common structural building materials are timber, concrete and steel.

The most influencing changes for structural materials (resilience wise) are the following:

- Increase in moisture: Humidity, heavy rainfall etc. due to increase in corrosion and wetting of wood.
- Increase in temperature leading to increased degradation of materials
- Subsidence leading to setting, shifting and instability
- Flood leading to severe impact damage

Flood damage and temperature influence have been assumed to be the priority for this thesis and further investigated on how to assess the influence.

Upon investigating a method for flood assessment, deflection calculations based on the FEMA coastal construction handbook are used to simulate flooding damages while evaluating the effect of a flood on a structure. Damage evaluation uses calculations generated from reference cases. The Hazus databases, the REDi rating system, and FEMA are used to calculate the recovery and repair times. These computations, formulae, and numbers may be written into the script for the tool.

In terms of temperature effect, an empirical concrete corrosion formula computes mass loss, whereas the Arrhenius equation may be used to assess the deterioration of wood and steel. A unique formula considering the concrete layer is needed to calculate concrete corrosion. Then, using Faraday's equation, corrosion ratios or material degradation ratios are transformed into mm/year. It is now possible to determine the new cross-section size and assess its effect on structural deflection by anticipating the mass loss. This loss is also directly tied to a structure's performance in flood, bringing both events investigated together.

Both these approaches are translated into a python script using packages such as open-meteo for climate data, klimaateffectatlas for flood depths and ifcopenshell for extracting data from IFC models.

The outcomes of both scripts are translated into a graph, both graphs can be combined to show how the events simultaneously happen.

REFLECTION & DISCUSSION

Throughout this research period, the biggest challenge was narrowing down the research to an achievable scope in the given time frame. I realize that some narrowing downs could've been made earlier, and I have found myself several times in a loophole where I was diving too much into the details of a topic. I learned that I am not the person that can keep surfaces unscratched because I tend to get overenthusiastic and dig deeper than the surface, leaving the surface scratched.

Apart from still managing the timeframe with my supervisors' help, I learned how to work with APIs, learn about the changes occurring, learn about material science more deeply: and most of all learn how to develop a tool and an assessment method. Ironically, in my previous study (bachelor) I had found myself unable to get an API work but now with the help of my supervisor, I was able to work with different APIs for the tool, so that made me happy and realize the progress that I've made throughout the years.

Generally, the tool works. It definitely serves its purpose of raising awareness and informing a designer of the consequences of climate change and their decisions. But it has a lot of room to improve or be developed further. This is especially due to the size of this topic and theme and the amount of knowledge and multidisciplinary aspects that play a role in climate change. I think the tool also lacks due to my lack of expertise: the numerous departments I've been touching with my topic are out of my knowledge and were new territories.

Throughout my research I genuinely felt like I was shifting from department to department. Initially I started with climate/weather science in my first subquestion, the sources I consulted were based on this department. This was especially the case because I was diving too deep into why the changes occurred.

Afterwards for subquestion 2, the Building Technology aspect came more into place with Material Science being the main theme.

Afterwards, for the development of the flood portion of the tool I shifted into Civil Engineering with the hopes of implementing their knowledge in a Building Technology scenario, and for the temperature, I moved into Material Science with Corrosion Technology and Electrochemistry.

And lastly for the development of the tool I embraced my inner software development motivation.

I genuinely loved this thesis theme because it allowed me to chase my curiosity in various topics. And I genuinely think that this describes me the best as an engineer: I'm an engineer who is enthusiastic for multidisciplinary knowledge, I enjoy chasing understanding of other departments and bringing them to mine, setting unique connections that otherwise wouldn't have been suggested at all. And I thank all my teachers that supported me throughout my journey for this growth of mine as an engineer :)

Regardless of the accomplishments and things I've learned, I've also realized and learned the critical aspects of my tool. These critical aspects will be described in their respective chapter below.

The future changes

Currently the data used is based on the klimaatsignaal of KNMI, and the old values from the klimaatsecnarios 2014. The newest klimaatsecnarios will be published around October 2023. In the near future the values used in this thesis and the tool need to be updated to the new scenarios of KNMI.

I am personally not expecting a great change in the predictions versus the scenarios, but it is still a value that may alter the outcome of the tools assessment. So updating this in the future is important.

The influences of climate change on structural performance

The matter of influences of climate change on structural performance is a very big topic and needed to be cut down to a feasible amount for the timeframe of this thesis. Each event has a lot of different correlated influences on a material, making each event a thesis worthy on itself because, for example, finding the correlation between temperature, humidity, and other environmental aspects in light of corrosion is disputed by different papers. So, in the end, this thesis focused on a more general tool that ended up making assumptions and leaving out aspects that could've been relevant. So, a future improvement on the current progress through this thesis would be a more in depth repeat of the sub questions with the available knowledge already.

What makes this tool great is that all these changes and calculations can then be added in the future, because this thesis aimed to provide the first loop/tool backbone. This backbone can easily be extended and developed further.

IFC Models

Before delving into IFC models I had expected that the standards for IFC had normalized a lot of parameters names. To my surprise, this was not the case and even amongst the software where these models were modeled, there was a clear difference in the data structure. This proved that the data extraction from IFC models is a more difficult process than it could have been the extraction of the data had to be from the model/shape's location instead of the parameters. I hope this will be changed in the future so data exchange can become easier.

Regardless in the end the IFC issue got solved, due to the help of my supervisor. Values in terms of geometry can be extracted through the shape's vertices. This might prove complication in particular cases and on the long run, but it at least does work.

The IFC data extraction can hopefully be improved when the information about objects becomes more readily available instead of hidden behind dictionaries with different titles.

The flood assessment

The flood assessment turned out to become something that merged both civil engineering knowledge and building technology knowledge. My background in building technology had not given me enough knowledge on this matter, but it had equipped me with the skills to be able to understand these civil engineering topics. Because of this, this aspect of my thesis became a very interesting merge of complex civil engineering calculations and predictions and simple hand calculations for designers in an early stage.

Some improvement suggestions can be made about the tool:

The tool can be expanded to take into consideration subsidence because future subsidence can lead to a higher flood height (An urban analysis is required because it might also lower the amount flooded due to different effects such as the gravity effect described in the previous chapter "Greenland & Arctic influences"). But since this topic Is broad enough to the extent that it requires a dedicated chapter, it wasn't implemented considering the research timeframe.

Another improvement is on the further expansion of the current assumptions that were made; different load cases or connections can be implemented in the code. Stress calculations can also be executed aside from checking the deformation.

Furthermore, the used values for the moment of inertia and elasticity modulus are limiting, this can be expanding by adding different shape selections or extraction from IFC and adding a values database.

Lastly, an advanced tool can be implemented, or past data specifically for the Netherlands can be used to assess the damage done. Currently, the damage assessment is based on data from Italy and is only applied when the deformation amount is exceeded. The deformation occurring also needs to be expanded with buckling and/or max deformation theory. The current tool assumed various circumstances where these weren't applicable or needed.

One complication that arose during the usage of the script was that some outer urban living areas outside of the city aren't seen as villages but plains. Another method for assessing the type of location should be researched further.

Apart from all those listed, the flood assessment only assesses direct flood damage, not what the aftermath could cause to the materials. For example, wood being an organic material would be more prone to damage from exposure to water and possible chemicals for a long period. The materials each being assessed on the damage that could arise from flood water submersion would greatly improve this assessment. This specifically for the fact that one material might be good for the damage, but bad for the submersion phase (Although this does not seem to be the case for steel based on the material research done pre assessment framework development).

The temperature assessment

The temperature assessment was a hard to bite through one for me personally. This is because all the influences that occur due to temperature are either hard to quantify with an empirical formula (for example things such as mold forming) or the fact that it is a chemistry process.

Because of this, I had to delve into a very unknown territory for me and learn about formulas in chemistry to still be able to assess the direct influence of temperature on degradation of materials. This made the temperature assessment a very unexpected multidisciplinary chapter.

For me personally, the temperature assessment is the most complicated portion of this thesis. This is because the calculations used for this are extremely new and out of my field. Currently the results within the script most likely have rounding up mistakes or other likewise issues. This is also the reason why the script's results weren't written as part of this thesis.

The key improvement points for temperature assessment would be fixing the usage/units of the formulas for each material. The theoretical part is set, but the backend coding is not progressed enough.

The tool

I had never expected to visually code with Python since the norm is that other coding languages are opted for interface developments. So being able to develop an interface with the coding language I personally feel most familiar with, was a great experience.

Although the 3D viewer was not implemented in the end due to technical difficulties, I hope this will become easier In the future with the growth of IFC models. Because being able to implement a 3D viewer with python would make the development of similar tools or the further development of this tool way more impactful and accessible for experts in different fields who do not know how to code.

BIBLIOGRAPHY

A. Sterl, H. v. (2009). *An ensemble study of extreme storm surge related water levels in the North Sea in a changing climate.* De Bilt: Royal Netherlands Meteorological Institute (KNMI).

Anikó Csébfalvi, A. L. (2020). *THE CLIMATE IMPACT ON TIMBER STRUCTURES.* Iran University of Science & Technology.

ASTM Standard . (n.d.). Calculation of Corrosion Rate. Retrieved from https://www.gamry.com/Framework%20Help/HTML5%20-%20Tripane%20-%20Audience%20A/Content/EFM/Introduction/Calculation%20of%20Corrosion%20Rate.htm

Auwalu, A., Noor, N., Ahmad Shah, M., Umar, S., Amran, M., Adamu, M., . . . Fediuk, R. (2022). *Performance of Steel-Bolt-Connected Industrialized Building System Frame Subjected to Hydrodynamic Force.* doi:https://doi.org/10.3390/app12105093

AXA UK. (2022, July 14). *What is subsidence and its signs?* Retrieved from https://www.axa.co.uk/home-insurance/tips-and-guides/spotting-the-signs-of-subsidence/#:~:text=Subsidence%20is%20a%20severe%20problem,and%20destabilisation%20of%20your%20house

BARKAS, W. W. (1935). *Fibre Saturation Point of Wood.* Nature.

Bernice Mizzi, Y. W. (2018). Effects of climate change on structures; analysis of carbonation-induced corrosion in Reinforced Concrete Structures in Malta.

Bert Metz, O. D. (2005). *IPCC Special Report on Carbon dioxide Capture and Storage.* Cambridge: Cambridge University Press.

Business Insider. (2018, September 11). 'Levensduur woning minimaal 120 jaar'. Retrieved from https://vastgoedactueel.nl/levensduur-woning-minimaal-120-jaar/#:~:text=Levensduur%20van%20een%20huis%2055%20tot%20500%20jaar&text=%E2%80%9CEen%20huis%20kan%20tussen%20de,gemiddelde%20levensduur%20van%20120%20jaar

Canadian Wildlife Health Cooperative. (n.d.). *PERMAFROST THAWING AND THE RISK OF EMERGING.*

Carvalho, H. M. (2019). Fatigue Analysis of a Concrete Chimney Under Wind Loads. *Mechanical Fatigue of Metals. Structural Integrity, vol 7. Springer, Cham*.

CBS, PBL, RIVM, WUR. (2002, October 8). *CO2-concentratie (kooldioxide), 1980-2001*. Retrieved from clo.nl: https://www.clo.nl/indicatoren/nl021603-broeikasgasconcentraties-mondiaal

Chen, X. (2016). *Impacts of overtopping waves on buildings on coastal dikes.* doi:https://doi.org/10.4233/uuid:e899b6e4-fcbe-4e05-b01f-116901eabfef

Christoph Keuschnig, C. L. (2022). *Reduced methane emissions in former permafrost soils driven by vegetation and microbial changes following drainage.* John Wiley & Sons Ltd.

Clemens-Preisinger. (2022, November 25). *Karamba3D 3.0.0.4-WIP*. Retrieved from GitHub: https://github.com/karamba3d/K3D_NightlyBuilds/releases/tag/3.0.0.4-WIP

Climate.gov. (2020, October 29). Retrieved from https://www.climate.gov/news-features/climate-qa/doesnt-carbon-dioxide-atmosphere-come-natural-sources#:~:text=Yes%2C%20there%20are%20natural%20sources,even%20belches%20from%20ruminant%20animals.

Cole, I. (2010, February). Possible effects of climate change on atmospheric corrosion in Australia. *Corrosion Engineering Science and Technology*, pp. 45(1):19-26. doi:10.1179/147842209X12579401586483

Corrosion Doctors. (2012, August). *Factors Affecting Atmospheric Corrosion*. Retrieved from corrosion-doctors.org: https://corrosion-doctors.org/Corrosion-Atmospheric/Factors-atmospheric.htm

D.A. Paterson, R. S. (1994). Hail impact on building envelopes. *Journal of Wind Engineering and Industrial Aerodynamics, Volume 53, Issues 1–2*, 229-246.

Dániel Honfi, A. R. (2014). Why glass structures fail? - Learning from failures of glass structures. *Challenging Glass 4 & COST Action TU0905 Final Conference.* Taylor & Francis Group, London.

De Wilde, P. &. (2012). The implications of a changing climate for buildings. Building and Environment, 55, 1–7.

Deltares. (2020). Impact droogte op funderingen.

Deltares. (2020). Systematic assessment of damage to buildings due to groundwater lowering-induced subsidence: methodology for large scale application in the Netherlands.

Derbyshire, H. M. (1981). *The photodegradation of wood during solar irradiation.*

FEMA. (2011). Coastal Construction Manual. FEMA.

FEMA. (n.d.). Performance Assessment Calculation Tool (PACT). FEMA. Retrieved from https://femap58.atcouncil.org/pact

Gilbert Gedeon, P. (2011). Coastal Construction - Determining Site-Specific Loads. In *COASTAL CONSTRUCTION MANUAL.* Retrieved from https://www.cedengineering.com/userfiles/Determining%20Site-Specific%20Loads.pdf

Hansson, E. F. (2011). Analysis of structural failures in timber structures: Typical causes for failure and failure modes. *Engineering Structures, Volume 33, Issue 11*, 2978-2982.

Hardwood Distributors Association. (n.d.). *Why Does Dried Wood Absorb Moisture?* Retrieved from Hardwood Distributors Association: http://www.hardwooddistributors.org/postings/why-does-dried-wood-absorb-moisture#:~:text=Wood%20is%20hygroscopic%2C%20which%20means,causing%20the%20wood%20to%20expand.

Hashim, F. &.-b.-A. (2020). Inhibition Effect of Hydrazine-Derived Coumarin on a Mild Steel Surface in Hydrochloric acid. *Finnish Journal of Tribology*, 37.

Hongbo Liu, X. L. (2015). Thermal behavior of spatial structures under solar irradiation. *Applied Thermal Engineering, Volume 87*, pp. 328-335. doi:https://doi.org/10.1016/j.applthermaleng.2015.04.079

Hongbo Liu, Z. C. (2012). *TEMPERATURE DISTRIBUTION AND STRUCTURAL BEHAVIOR OF BOX-SECTIONAL ARCH STRUCTURES UNDER SOLAR RADIATION .*

Hongbo Liu, Z. C. (2014). Study on the thermal behavior of aluminum reticulated shell structures considering solar radiation. *Thin-Walled Structures, Volume 85*, pp. 15-24. doi:https://doi.org/10.1016/j.tws.2014.07.007

Ibrahim Almufti, M. W. (2013). *Resilience-based Earthquake Design Initiative (REDi™) Rating System.* ARUP.

Industrial Metallurgists, LLC. (n.d.). *Industrial Metallurgists, LLC*. Retrieved from Hydrogen Embrittlement of Steel: https://www.imetllc.com/hydrogen-embrittlement-steel/

IPCC. (2021). *Climate Change 2021: The Physical Science Basis. Working Group I Contribution to the IPCC Sixth Assessment Report.* United Kingdom and New York: Cambridge University Press.

Jacob Stolle, N. G. (2018). *Handbook of Coastal and Ocean Engineering.* Department of Civil Engineering University of Ottawa,Ottawa, Canada.

Jansen, L. (2019). *Structural damage to Dutch terraced houses due to flood actions.* Delft. Retrieved from https://repository.tudelft.nl/islandora/object/uuid%3Ae03eacd3-1db0-4f83-81b9-57b994256c0a?collection=education

Jelger Arnoldussen, G. R. (2020). Materiaalstromen, milieu-impact en energieverbruik in de woning- en utiliteitsbouw.

Katja Woth, R. W. (2006). *Climate change and North Sea storm surge extremes: An ensemble study of storm surge extremes expected in a changed climate projected by four different Regional Climate Models.* Online: Springer-Verlag.

KLAASSEN, R. K. (2015). Life Expectation of Wooden Foundations - a Non-Destructive Approach .

KNMI. (2014). Retrieved from KNMI'14-klimaatscenario's: https://www.knmi.nl/nederland-nu/KNMI14_klimaatscenarios/kerncijfers

KNMI. (2015). *KNMI'14-klimaatscenario's voor Nederland; Leidraad voor professionals.* De Bilt: KNMI.

KNMI. (2021). *KNMI Klimaatsignaal'21: hoe het klimaat in Nederland snel verandert.* De Bilt: KNMI.

Koninklijk Nederlands Meteorologisch Instituut (KNMI). (2022). *weerstatistieken*. Retrieved from https://weerstatistieken.nl/de-bilt/2022

Kramar, T. P. (2015, September 1). Traditional Timber Structures in Extreme Weather Conditions. pp. Pages 689-695.

Lamond, D. P. (2017). *Flood Resilient Construction and Adaptation of Buildings.*

Lanser, M., Amde M. Wolde-Tinsae, M. A., & and Lowell F. Greimann, M. A. (1984). Effects of Lightning on Concrete. *Journal of Structural Engineering*.

LCETED INSTITUTE FOR CIVIL ENGINEERS. (2021). *Concrete Failure | Causes Of Concrete Structure Damage | Types Of Concrete Failure*. Retrieved from Concrete Failure | Causes Of Concrete Structure Damage | Types Of Concrete Failure

Li, J. L. (2021). *Examination of Lightning-Induced Damage in Timber.* IntechOpen. doi:10.5772/intechopen.99644

London Image Institute. (2020). *Color Psychology: How Do Colors Affect Mood & Emotions?* Retrieved from London Image Institute: https://londonimageinstitute.com/how-to-empower-yourself-with-color-psychology/

Lu, C. R., Ge, X. L., Mei, G. X., Liu, W. B., Wang, H., & Qian, Y. L. (2011). Effect of

Drought on Dry Shrinkage of Cementitious Materials . *Advanced Materials Research (Volumes 261-263)*, 606-610. Retrieved from https://www.scientific.net/AMR.261-263.606

Mark G. Stewart, E. B.-A. (2019). Chapter Four - Corrosion of Concrete and Steel Structures in a Changing Climate. In E. B.-A. Mark G. Stewart, *Climate Adaptation Engineering* (pp. 99-125). doi:https://doi.org/10.1016/B978-0-12-816782-3.00004-8

Mattia Amadio, A. R. (2019). Testing empirical and synthetic flood damage models: the case of Italy. *Natural Hazards and Earth System Sciences*. doi:https://doi.org/10.5194/nhess-19-661-2019

Meng Zhou, J.-S. F.-F.-X.-J.-S. (2020,). Non-uniform temperature field and effect on construction of large-span steel structures. *Automation in Construction, Volume 119*. doi:https://doi.org/10.1016/j.autcon.2020.103339

Mercer, E. (2017). *What Is the Molar Mass of Steel?* Retrieved from Sciencing: https://sciencing.com/molar-mass-steel-10067961.html

Mindess, S. (2007). *Environmental deterioration of timber.* Canada: University of British Columbia, Canada.

Minh N Nguyen, X. W. (2013). An Assessment of Climate Change Effects on Atmospheric Corrosion Rates of Steel Structures. *Corrosion Engineering Science and Technology*, 48(5):359 - 369. doi:10.1179/1743278213Y.0000000087

Missouri University of Science and Technology. (2016). *Full-Scale Experimental and Numerical Study about Structural Behavior of Thin-W vior of Thin-Walled Cold-F alled Cold-Formed Steel Building aff ormed Steel Building affected b ected by Ground Settlements due to Land Subsidence.*

NASA. (2019, October 9). *https://climate.nasa.gov/*. Retrieved from https://climate.nasa.gov/news/2915/the-atmosphere-getting-a-handle-on-carbon-dioxide/#:~:text=Once%20it's%20added%20to%20the,timescale%20of%20many%20human%20lives.

NASA's Jet Propulsion Laboratory. (2019, October 9). *The Atmosphere: Getting a Handle on Carbon Dioxide*. Retrieved from NASA Global Climate Change: https://climate.nasa.gov/news/2915/the-atmosphere-getting-a-handle-on-carbon-dioxide/#:~:text=Carbon%20dioxide%20is%20a%20different,between%20300%20to%201%2C000%20years.

National Steel Buildings. (n.d.). *A GUIDE TO METAL BUILDINGS AND LIGHTNING SAFETY*. Retrieved from nationalsteelbuildings: https://nationalsteelbuildings.co.uk/a-guide-to-metal-buildings-and-lightning-safety/

NEN. (2021). *Energy performance of buildings - Determination method.* NEN.

Paterson, I. S. (2010). Possible effects of climate change on atmospheric corrosion in Australia. *Corrosion Engineering, Science and Technology, 45*.

PhD, D. V. (2002). *Performance of timber buildings under high wind loads.*

plantchicago. (2018, January 17). *Thinking Circular, with Chemistry*. Retrieved from plantchicago: https://www.plantchicago.org/post/thinking-circular-with-chemistry#:~:text=In%20actuality%20w ood%20is%20mostly,formula%20is%3A%20C6H12O6%20%2B%20Ca

Polygon. (n.d.). *Can Mold Grow on Concrete?* Retrieved from https://www.polygongroup.com/en-US/blog/can-mold-grow-on-concrete/

Price, C. (2009). Thunderstorms, Lightning and Climate Change. In C. Price, *Lightning: Principles, Instruments and Applications* (pp. 521–535). Retrieved from https://link.springer.com/chapter/10.1007/978-1-4020-9079-0_24

Rijksoverheid. (2021, November 9). *Ecosystem quality and trends in soil pH, 2018*. Retrieved from https://www.clo.nl/indicators/en1593-ecosystem-quality-and-trends-in-soil-ph

Rijkswaterstaat. (2023, January). *Rijkswaterstaat Bodem+*. Retrieved from Rijkswaterstaat Bodem+: https://www.bodemplus.nl/onderwerpen/bodem-ondergrond/bodemdaling/

Roberge, P. R. (2000). *Handbook of Corrosion Engineering.* McGraw-Hill.

Roser, H. R. (2021). *https://ourworldindata.org*. Retrieved from Netherlands: CO2 Country Profile: https://ourworldindata.org/co2/country/netherlands

Rosowsky, D. V. (2002). *Performance of timber buildings under high wind loads.*

Semenenok, S. (1969). Effect of solar radiation on the temperature regime of concrete masonry. . *Hydrotechnical Construction 3*, S. N. Semenenok .

SFIA. (2018). *Cold-Formed Steel And Resilience.* Retrieved from https://sfia.memberclicks.net/assets/LEED/Resilient%20CFS%2010.4.pdf

Shi, R. Z. (2023). *Research on Corrosion Rate Model of Reinforcement in Concrete under Chloride Ion Environments.* doi:https://doi.org/10.3390/buildings13040965

Shuxian Hong, F. Z. (2020). Determination of impressed current efficiency during accelerated corrosion of reinforcement. *Cement and Concrete Composites, 108*. doi:https://doi.org/10.1016/j.cemconcomp.2020.103536.

Soria, A. &. (2016). Modeling of the pyrolysis of biomass under parabolic and exponential temperature increases using the Distributed Activation Energy Model. *Energy Conversion and Management*, 223-230.

Steenbergen, R. K. (2012). The effect of climate change and natural variability on wind loading values for buildings. Building and Environment, 55, 178–186.

Stichting Climate Adaptation Services (CAS). (2023, January). *klimaateffectatlas*. Retrieved from klimaateffectatlas: https://www.klimaateffectatlas.nl/nl/bodemdalingsvoorspellings-kaarten

Structural Guide. (n.d.). *20 Factors Affecting Durability of Concrete*.

Structville Integrated Services. (2021, August 30). *Effect of Groundwater Table on the Bearing Capacity of Shallow Foundations*. Retrieved from https://structville.com/2021/08/effects-of-groundwater-table.html

Sundararaj, R. (2022). *Science of Wood Degradation and its Protection.* Bangalore.

Telegraaf. (2022). *Honderden doden door hittegolf in Spanje en Portugal*.

thyssenkrupp. (n.d.). *Does stainless steel rust?* Retrieved from https://www.thyssenkrupp-materials.co.uk/.

U.S. Department of Health & Human Services. (2022). *Floodwater After a Disaster or Emergency.*

United Nations Environment Programme. (2021). *A Practical Guide to Climate-resilient Buildings & Communities.* Nairobi: United Nations Environment Programme (UNEP). doi:ISBN: 978-92-807-3871-1

Vagapov, R. I. (2020, November). Corrosion Processes on Steel Under Conditions of Moisture Condensation and in the Presence of Carbon Dioxide. *Chem Petrol Eng*, pp. 673–680. doi:https://doi.org/10.1007/s10556-020-00825-5

van Haren, M. (2021). *Flood Fragility of a Cavity Wall: Experimental results on the deformations of a window-featured cavity wall due to hydrostatic flood actions and failure of the window-wall interface.* Delft. Retrieved from https://repository.tudelft.nl/islandora/object/uuid%3A2a56652d-8c10-4610-b90c-5d83dda286ff?collection=education

VENTA WINDOWS. (n.d.). *Venta Windows*. Retrieved from https://ventawindows.com/wp-content/uploads/2019/07/Glass_unit_thermal-mechanical_breakage_EN_mail3.pdf

Weck, R. (1965). *Failure of steel structures: causes and remedies.* Proc. R. Soc. Lond. doi:http://doi.org/10.1098/rspa.1965.0084

Wei-Jia Liu, Y.-S. T.-B.-F.-F.-J. (2022). Influences of short-term heavy rainfall on interlayer properties and microstructure of concrete dam. *Case Studies in Construction Materials, Volume 17*.

Weyerhaeuser Company. (2018). *What is Allowable Deflection ?* Retrieved from Weyerhaeuser.

Xin Ge, Y. G. (2018). Effect of low air pressure on the durability of concrete. *Construction and Building Materials Volume 187*, 830-838.

XIONG WU, W. Y. (2021). EFFECT OF LOW PRESSURE ON THE PROPERTIES AND MICROSTRUCTURE OF ULTRA-HIGH PERFORMANCE CONCRETE.

Xu, W. D. (2020). Non-Uniform Temperature Fields and Effects of Steel Structures: Review and Outlook. *Advances on Structural Engineering*. doi:https://doi.org/10.3390/app10155255

Yawei Lu, Z. W. (2020, December). Experimental studies on influencing factors of stress corrosion in rectifying column. *Process Safety and Environmental Protection*, pp. 123-132. doi:https://doi.org/10.1016/j.psep.2020.07.029

Zhang, S., Tian, B., Chen, B., Lu, X., Xiong, B., & Shuang, N. (2022). The Influence of Freeze–Thaw Cycles and Corrosion on Reinforced Concrete and the Relationship between the Evolutions of the Microstructure and Mechanical Properties.

Zhongwei Zhao, H. L. (2016). *FIELD MONITORING AND NUMERICAL ANALYSIS OF THERMAL BEHAVIOR OF LARGE SPAN STEEL STRUCTURES UNDER SOLAR RADIATION .* State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University.

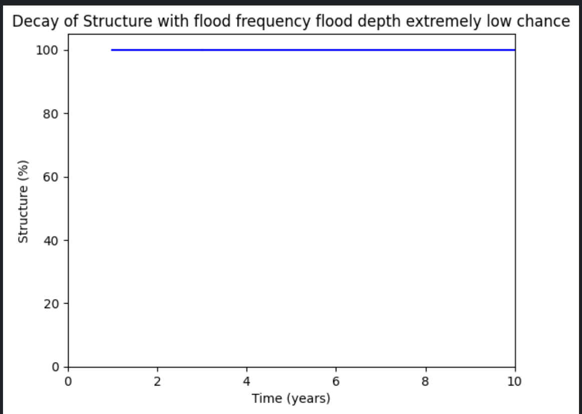
Zibo Pei, X. C. (2021). Understanding environmental impacts on initial atmospheric corrosion based on corrosion monitoring sensors. *Journal of Materials Science & Technology*, 214-

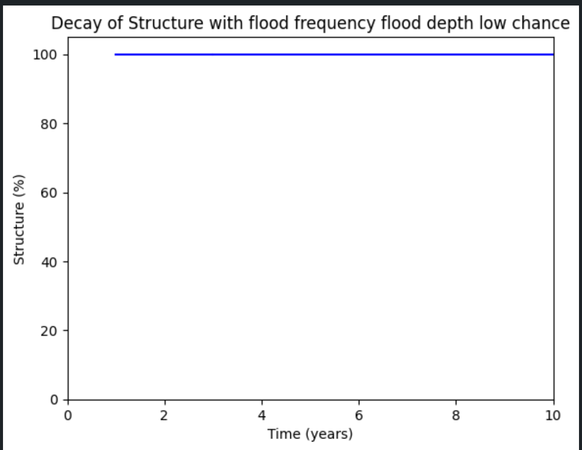
221.
doi:https://doi.org/10.1016/j.jmst.2020
.01.023

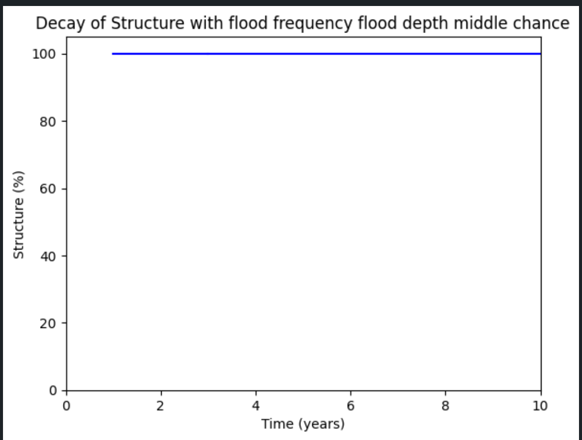
APPENDIX

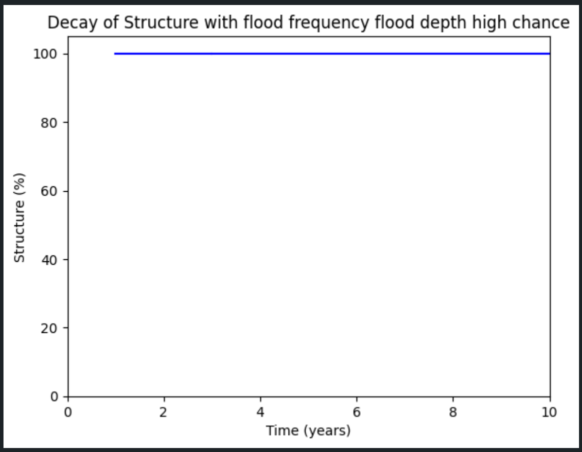
APPENDIX A: GRAPHS FROM FLOOD DAMAGE

Location 1: Delft TU Delft Bouwkunde

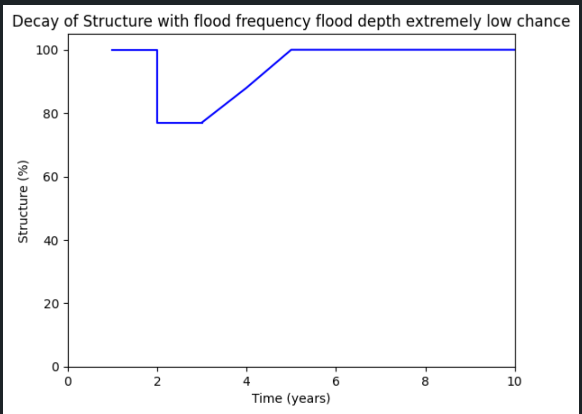


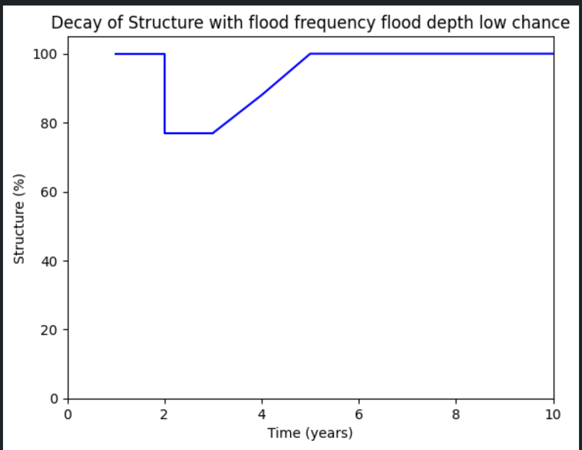


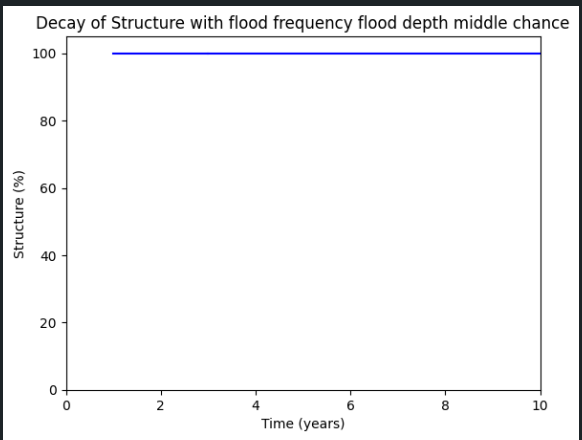


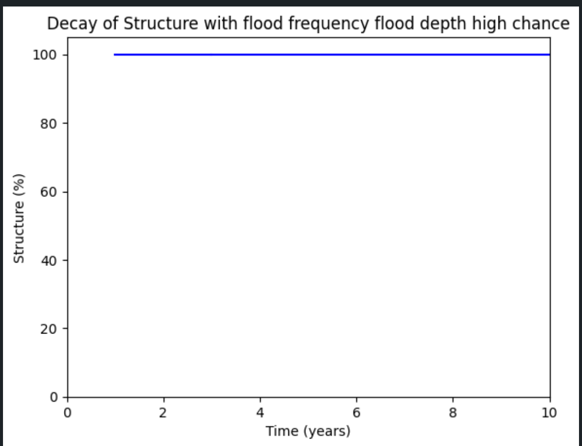


Location 2: A random plain in Gorinchem

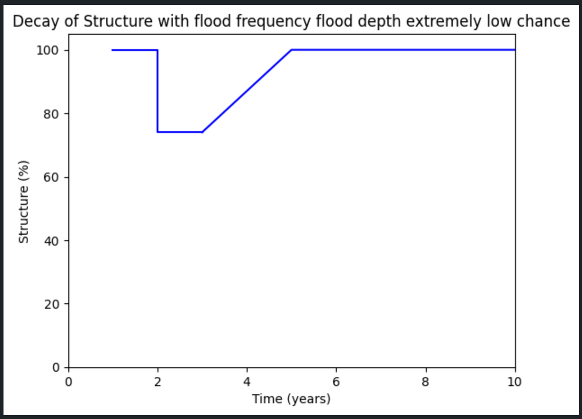


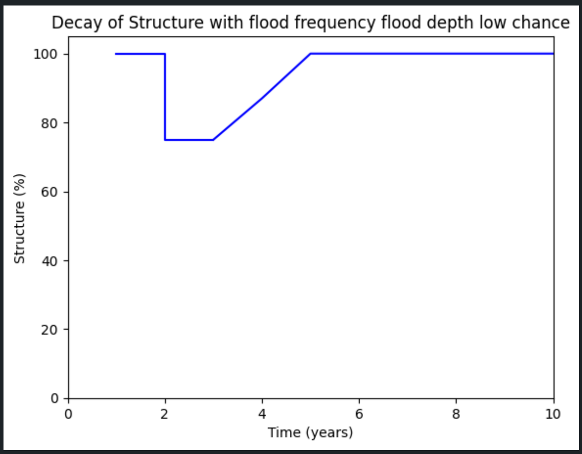


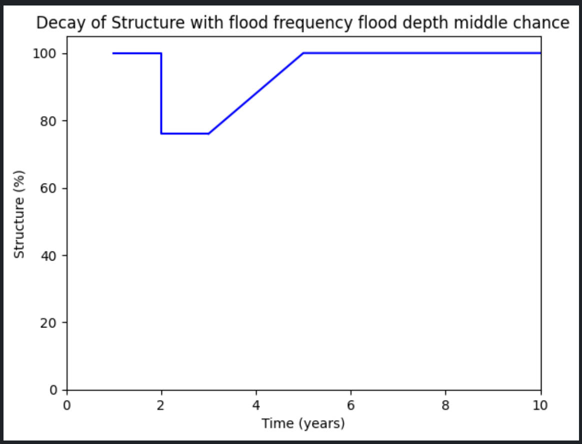


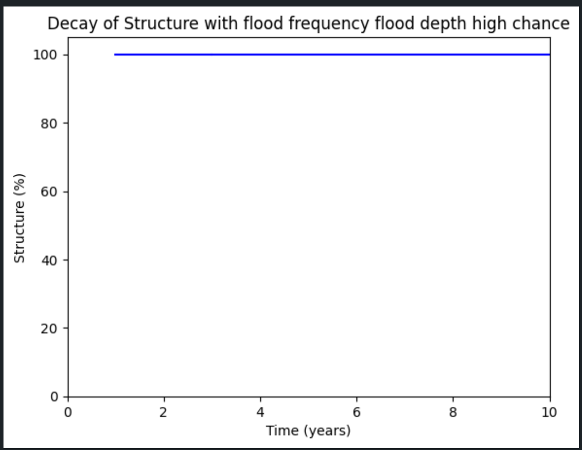


Location 3: Landgoed de Brouwketel in Angeren

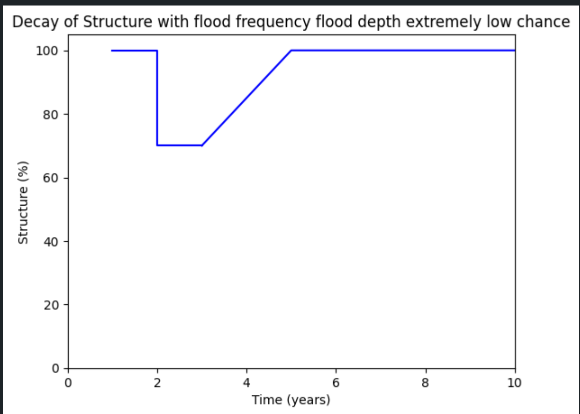


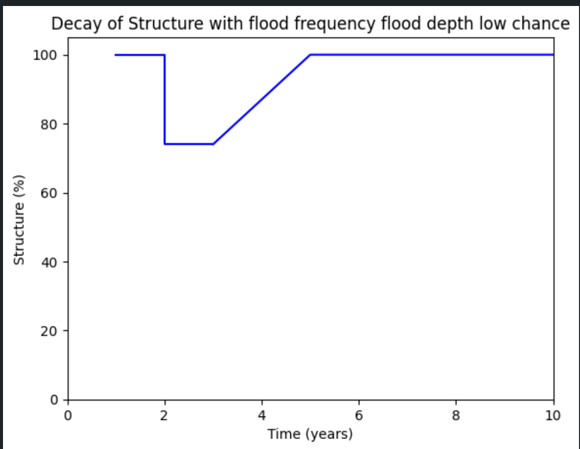


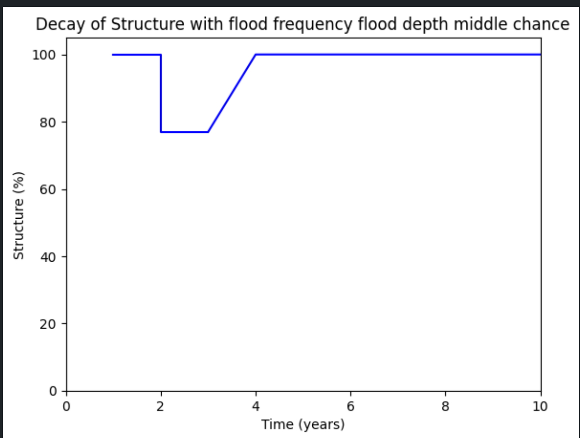


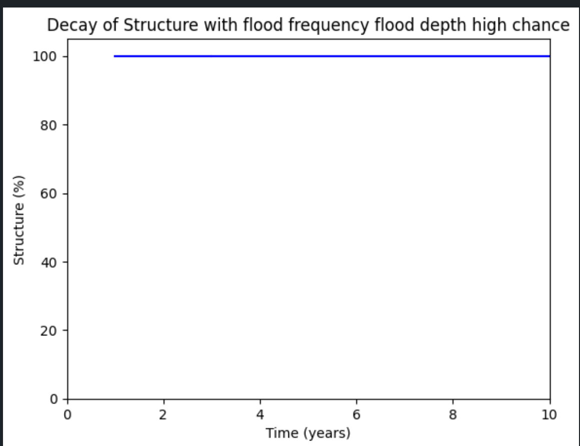


Case 3: Fictional location Wood

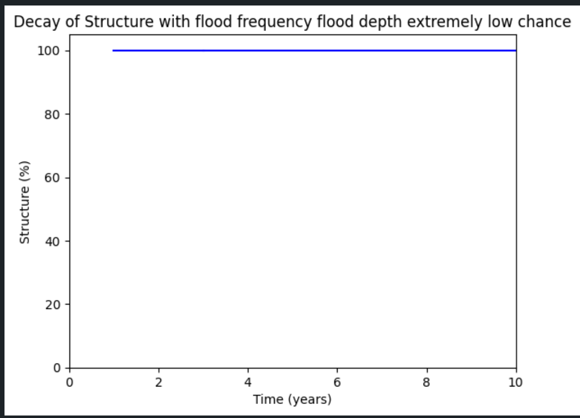


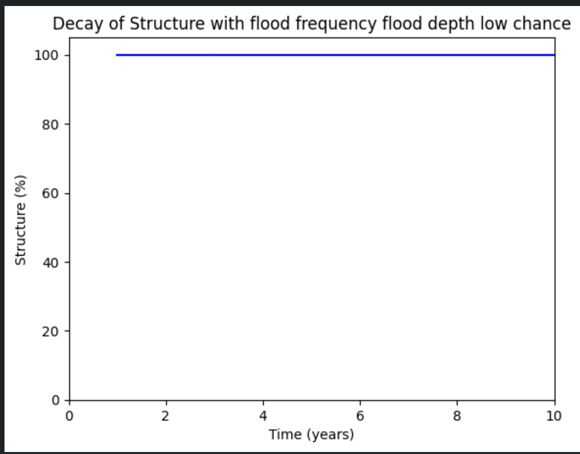


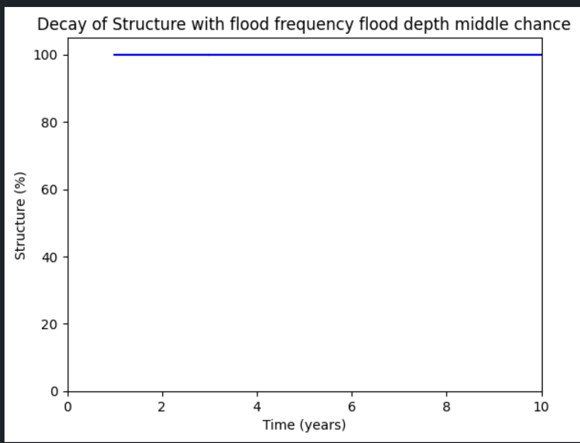


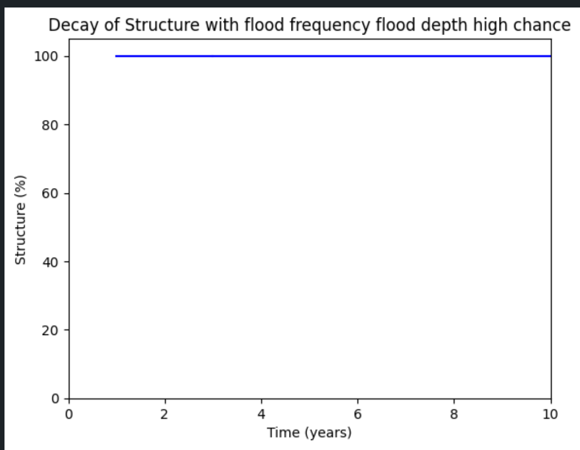


Case 3: Fictional location Steel









Case 3: Fictional location Concrete