Synergy of urban ventilation & flood defence

Hao Yan

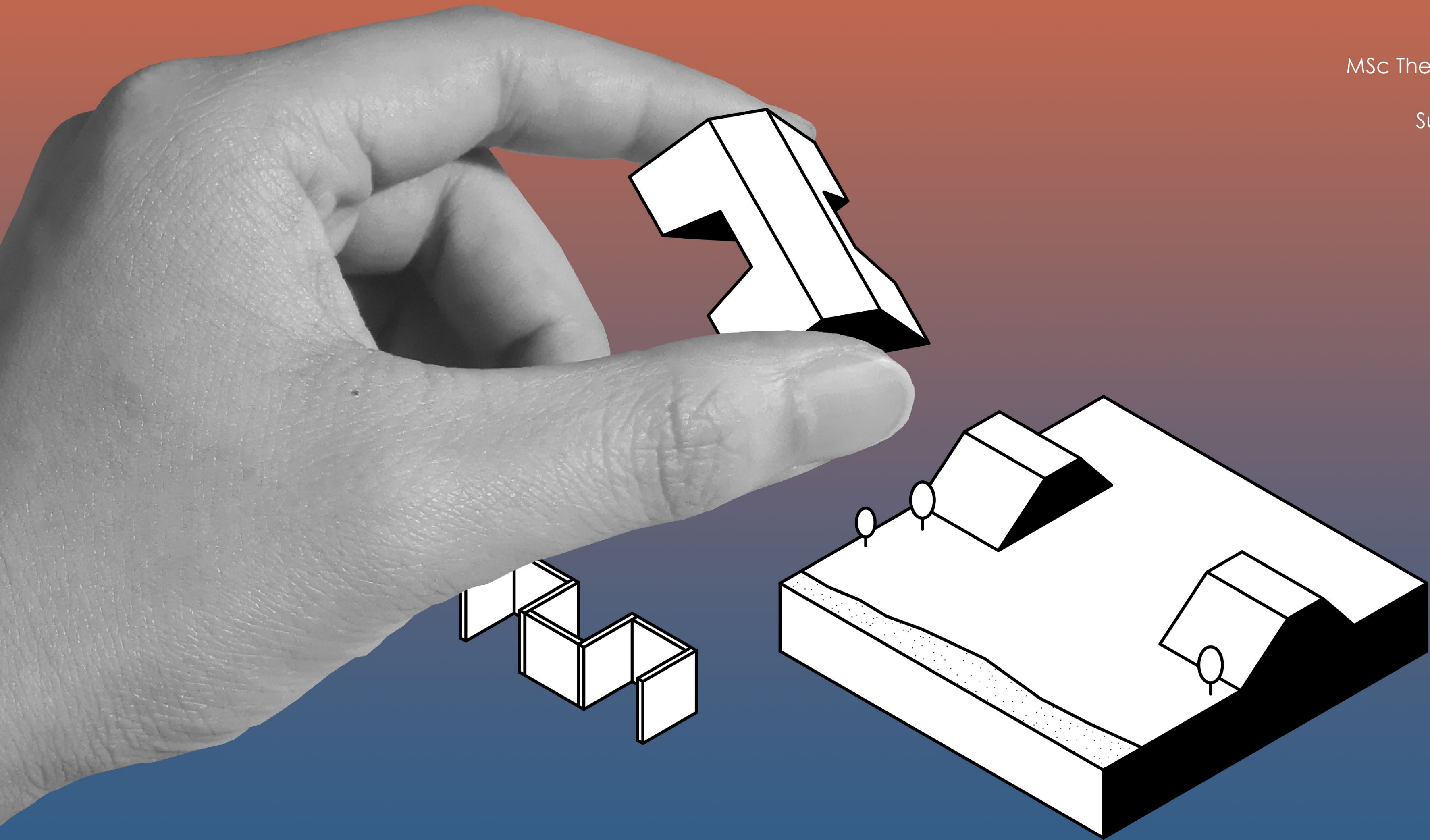
MSc Thesis Landscape Architecture

Reg.N: 940314980020

Supervisor: Sanda Lenzholzer

April 2020

Wageningen University



Synergy of urban ventilation and flood defence

Hao Yan
MSc Thesis Landscape Architecture
Reg.N: 940314980020
Supervisor: Sanda Lenzholzer
April 2020
Wageningen University

Landscape Architecture Chair Group
Phone: +31 317 484 056
Fax: +31 317 482 166
E-mail: office.lar@wur.nl www.lar.wur.nl

Postbus 47
6700 AA, Wageningen
The Netherlands

PREFACE

The thesis is a summary to my 3-year Master study, which took me eleven months. The optional course of climate-responsive design in the first year of the Master program gave me the first insight into the fact that landscape architecture should be informed by micro-climate knowledge. Later on, the urban hydrometeorology course enabled me to analyze climatic problems and resource in a technical way. Gradually, design with microclimate became the track of my Master study. While my knowledge was accumulating, I have witnessed climate change hitting mankind in the way that everyone has underestimated. Hurricanes, forest fires, crazy heat waves and the conjectural relationship with virus outbreaks. I realized humans are vulnerable to it in ways none of us can imagine and started to believe design with climate, like Noah's Ark which protected creatures from the flood, is able to ensure people to stay outdoor during climate change.

With the great passion for landscape architecture and the deep will to fill up the knowledge gap, I completed this thesis. I am so glad I had the scientific attitude of an urban climate researcher in the former part and the creativity of a designer in the latter half of this thesis.

I would like to thank my supervisor Sanda Lenzholzer who enlightened me for urban climate with her indispensable guidance and the high expectation she had on me from the beginning. My thanks also goes to João Cortesão for his meticulous advice and huge interest in my topic. Also, I deliver my thanks to my 'colleagues' at the Climatelier who are fully equipped with urban climate knowledge. Thanks to my family that supports me mentally and financially all the time. And thanks go to my friends who sometimes pulled me out when I was struggling in the mire of my thesis.

Haoyan

Supervisor & Examiner:
prof.dr. S (Sanda) Lenzholzer dipl.ing.MA
Professor and chair of the Landscape Architecture Group
Wageningen University & Research

Examiner:
JP (João) Antunes Granadeiro Cortesão PhD
Universitair docent Landscape Architecture
Wageningen University & Research

ABSTRACT

Urban climate is strongly related to topographies. The urban heat island is happening in the urban fabric when cold air zones appear in the open and green landscape. Due to climate change and urbanization, the urban heat island effect would hit more people harder. Therefore any potential urban cooling resources should be utilized. Thermal-driven winds or the so-called 'cool breeze' between floodplains and built-up areas is highly valuable.

In order to invite the cool breeze into Dutch cities, the dike that is currently playing the role of a barrier needs to be altered. A seasonal flexible flood defence alternative is believed to be possible because the need of flood defence (winter to spring) and urban cooling (summer) never occur at the same time.

To study the characteristics of the cool air exchange between the floodplain and the urban area and the hampering effect of the dike, the microclimate simulations were made through ENVI-met for the testbed. The simulations indicated that the cool breeze is happening between different topographies where the temperature difference occurs, and has the significant cooling effect to air temperature in the neighbourhood. According to the findings of the microclimate simulations, eight concept models were designed based on the idea of opening for ventilation and closing for flood protection. Along with the research through design process, these alternatives were improved, detailed and selected. Eventually, the inflatable dike partition, the modular & moveable floodwall and the gabion dike were considered to have the best performances in urban ventilation and the most stable structures for flood defence. After that, they were applied in the site-specific landscape design in order to explore social multifunctions the new structures could provide.

At the end of the research, three prototypes of the adjustable flood defence structure were generated to replace the traditional dike in Dutch cities, where heat problems is adjacent to the floodplain. In addition, both the neighbourhood-oriented and tourist attractive multifunctions were identified for each alternative.

Keywords:
Urban microclimate, Multifunctional flood defence, UHI Mitigation, Floodplain, Thermal-driven wind, Dike

CONTENTS

1 Introduction

1.1 Introduction

Urban heat island effect

The densely built-up urban area is normally warmer than its surrounding arable fields and natural areas, which is mostly caused by its fabric that traps radiation. Longwave radiation is more effective, so urban island effect is stronger during the night. The air temperature difference is also caused by less evaporation and transpiration in the city due to less open soil, water and plants. Besides, less ventilation, more heat storage in urban materials and anthropogenic heat also contribute to the UHI (Buyantuyev & Wu, 2010). For Dutch cities, the UHI effect has been measured and ranges from 3 to 10 °C (Albers, et al., 2015). As a result, the UHI strongly decreases the quality of outdoor space during summer (Van Hove et al., 2011). Half of the urban outdoor spaces expose to the heat stress annually more than one week, in big cities such as Rotterdam, it is normally more than two weeks (Albers, et al., 2015).

In reality, the UHI does not always appear in the city centre but distributes in many locations depending on topologies (Oke, et al., 2017). Therefore, the urban heat island is preferred to be called the urban heat archipelago (Lenzholzer, 2015). the UHI could appear in the high-rise and crowded commercial district in the city centre as well as the densely built-up and highly paved residential area on the riverside. Moreover, climate change might exaggerate the UHI, as well as the risk of flood and drought (Albers, et al., 2015).

'Open landscape' climatope

Land-uses, building materials, vegetation and different types of surfaces determine the typical microclimate characteristics, which is called climatopes (Scherer, Fehrenbach, Beha, & Parlow, 1999). In general, the urban land is categorized into 11 types of climatopes according to the climatic feature: (1) water, (2) 'open landscape', (3) forest, (4) park, (5) garden city, (6) city periphery, (7) city, (8) city centre, (9) commercial district, (10) industrial estate, and (11) railway yard climatope. The climatope map give an overview of the temperature situation (Lenzholzer, 2015). The city centre, the commercial district, the densely residential area and sometimes the industrial estate are places where urban heat island effect takes place. These areas usually have higher air temperature when low air temperature appears in the 'open landscape' climatope.

The open landscape has a relatively bigger sky view factor, which ensures that the heat stored from daytime can go back to sky in the form of longwave radiation after sunset. Moreover, the evaporation and transpiration from vegetation and soil also extract heat from air, which cools down the area faster than urban areas (Lenzholzer, 2015).

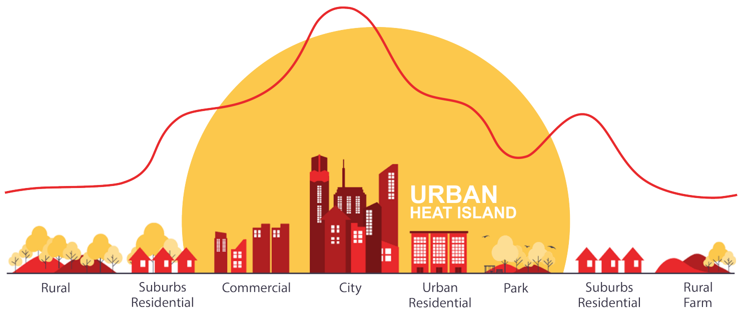


Figure 1.1.1 Urban heat island effect (Schmidt, 2018)

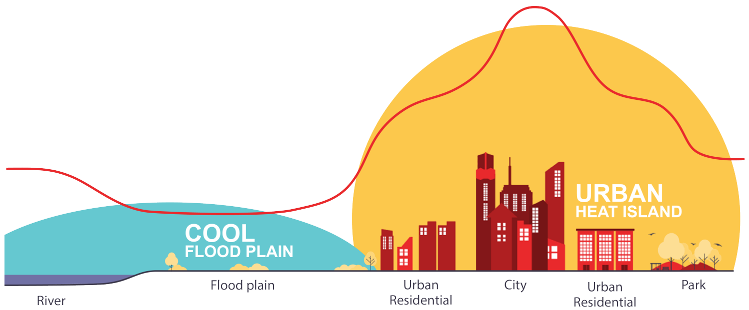


Figure 1.1.2 UHI effect adjacent to the floodplain

Breeze

In different climatopes, the temperature contrast results in different air pressure. If different climatopes are next to each other, the pressure contrast evokes the cool air movement from the lower temperature area to the higher. For example, at places where the city centre is adjacent to a floodplain, the light warm air goes up in the city centre, then leaves negative pressure on the lower level, which triggers the heavy cold air on the floodplain to move slowly into the city (Erell, Dennis., Williamson & Pearlmutter, 2011). It is believed that the cold air movement has great potential to mitigate the urban heat problem by functioning as natural ventilation.

Generally, at the place where the open green area is adjacent to the paved built-up area, the cool breeze is likely to happen. However, the valuable breeze is vulnerable, because the heavy cold air is moving very slowly just above the ground level. Therefore, it is easily interrupted or blocked by an obstacle in any forms. To let the cool breeze come into the city, the area where cool air originates from and the ventilation direction should be kept open (Lenzholzer, 2015).

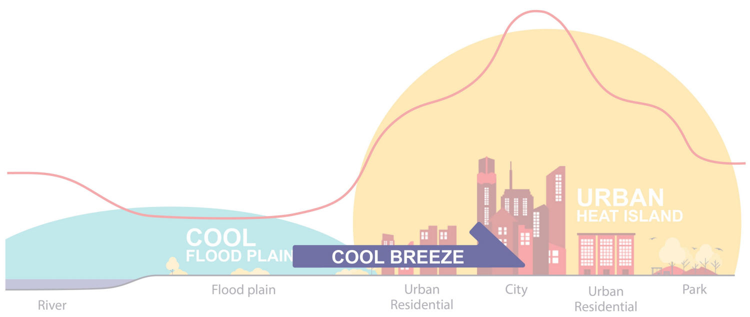


Figure 1.1.3 A cool breeze

1.2 Problem statement

It is a common meteorology phenomenon that different temperature zones result in pressure differences, which provoke many types of thermal-driven wind from the colder zone to the warmer (Serafin & Zardi, 2010). In mountainous terrains, after sunset, the mountain basin is trapping the heavy cold air down to it and creates a cold-air pool (Clements, Whiteman, & Horel, 2003). Hampering effect to air convection is also found in coastal cities where sand dunes are between the urban area and the coastal region (Lenzholzer, 2015). On a smaller scale, at the place where the urban green park is lower than the surroundings, the heavy cold air in the park is hard to spread (Lenzholzer, 2015). In the book 'Design with microclimate', cool-air pool effect is mentioned on a rather smaller scale. In the courtyard with a tree in the middle and surrounded by walls, the cool-air pool is also created because cool air with high-density can not go above the wall, even though the wall is only three-metre tall (Brown, 2010). Similarly to these examples, the dike between cities and adjacent floodplains plays the same role as the sand dune in the coastal city.

Figure 1.2.1 Mist on the floodplain due to contact of warm and cold air

As mentioned above, the cool air exchange between the urban climatope and the floodplain is very slow and vulnerable, therefore even trees, shrubs, houses, and dikes can have the hampering effect on it (Lenzholzer, 2015). In other words, the dike is restricting natural ventilation from the floodplain in most of the year, but only functioning as flood defence in limited time.

Due to climate change, the rising of sea level and the increasing amount of heavy rainfalls are challenging the traditional flood protection system. And longer and more extreme heat waves will hit urban areas harder by creating heat stress and deteriorating the quality of outdoor spaces. On the other hand, the population and property within the dike ring are determining the optimal height of the dike, according to the cost-benefit analysis of flood defence measures. It means that the denser and more crowded city should be protected by the dike of a higher safety norm (Eijgenraam, 2006). The fact that denser cities are protected by higher dikes leads to the downward spiral, which makes urban heat problems worse, because the higher dike minimize the opportunity of ventilation from the adjacent floodplain when the denser city cause stronger urban heat island effect.

As a result, urban heat problems in public spaces are getting worse in highly populated cities if no intervention is taken. The traditional dike ring system is a solution to flood, but it is becoming an obstacle to urban ventilation during climate change. It is necessary at this moment to explore the possibility that flood defence and urban ventilation can co-exist and promote each other.

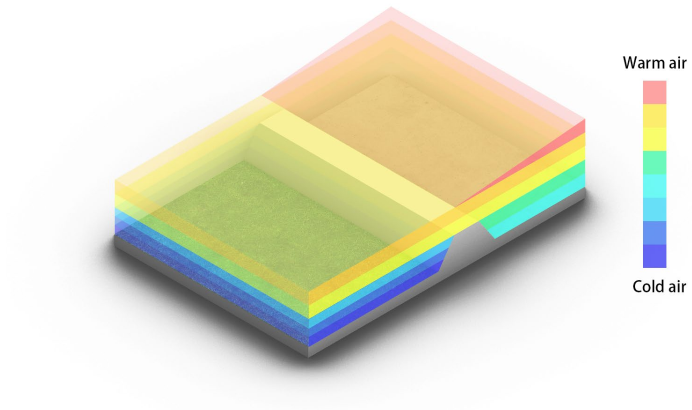


Figure 1.2.2 Cool-air pool effect

1.3 Knowledge gap

Thermal-driven wind and cool-air pool effect have been studied by many researches on mountain areas (Clements, Whiteman, & Horel, 2003), coastal cities, urban parks (Sugawara, et al., 2016) and even courtyards (Brown, 2010), but no literature focused on the influence of dikes or the microclimate interaction between dikes and floodplains. However, dikes are quite different from other examples, since they are not as tall as the mountain ridge, nor as steep as the wall.

So far, no research has quantitatively focused on how tall the dike is can have a significant effect on hampering the cool air exchange. Moreover, the floodplain is different from an urban park, since it has a larger skyview factor which is assumed to be better for cooling. Studying the thermal-driven air interaction and its relationship with three elements: the floodplain, the dike and the urban area contributes to the knowledge of urban microclimate.

On the other hand, with the concern about climate change and the thought of designing with nature, the role of the dike has been re-considered in many studies. It is possible and desirable to have an innovative relation between two sides of the dike, in order to serve more purposes (Meyer & Hermans, 2009). Plenty of possibilities of multifunctional uses of the dike have been explored and discussed in recent researches, but none of them has thought about combining it with urban climate improving, especially solving or mitigating urban heat problems. Exploring how the dike could let cool air to penetrate contributes to the knowledge of mitigation measures of the urban heat problem. Meanwhile seeking for potential social uses of the new structure broadens the scope of multifunctional flood defence.

1.4 Research objectives

The objective of this research through design is to make a pioneer attempt to coexistence and synergy of flood protection and urban climate improving, which is unlikely to happen in the current practical context due to safety and economic reasons.

This study aims to redefine the role of dikes, which is ingrained especially in Dutch people's mind, by designing a series of innovative but applicable multifunctional 'dikes' that only belong to the future when all possible measures are taken to mitigate and adapt to climate change. It is hoped that my design would help to bring up the awareness that landscape architecture should be informed by microclimate knowledge.

1.5 Research questions

The general research question for this study is:

> **MRQ: How can new types of river dike provide flood defence, urban ventilation and social functions?**

The general research question will be answered by answering the following hree sub-research questions:

> **SRQ1: To what extent does the dike hamper the cool air exchange?**

> **SRQ2: How can the adjustable dike structure optimize the flow of a cool breeze?**

> **SRQ3: What is the potential of adjustable dike structures to create places providing social functions?**

1.6 Research structure

The research structure was divided into two parts: Preparatory steps and Research through Design (RtD). In the phase of research through design, the three sub-research questions were supposed to be answered.

In the steps of preparation, the important task was to find a suitable site as the testbed for the later design. To do so the site selection criteria was formed through literature review and map study. Meanwhile, literature and reference cases about climate-responsive design and multifunctional flood defence were studied to establish the theoretical framework and further to develop the design hypothesis and the assessment criteria. The Research through Design was carried out through two design loops, followed by the explorative site design which respectively focuses on (1) microclimate, (2) structural stability and (3) social functions.

SRQ 1

At the beginning of Design Loop 1: microclimate, the first round of ENVI-met simulation was done to the two comparative models, one with the dike and the other without. The models were been built based on the abstracted topology of the testbed. The simulation software applied in this step was ENVI-met, which is able to simulate the urban climate process three-dimensionally based on the model that contains geometrical shapes, materials, and vegetation (Huttner, 2012). The first sub-research question was stepwise answered here by making comparisons of the simulation outcomes.

To further examine the ventilation effect of opening the dike, the second round of simulation was done to the intermediate situation, which was represented by the model with partly dike remained. By comparing the second outcomes with the first round, the first sud-research question (To what extent does the dike hamper the cool air exchange?) was answered.

SRQ 2

Based on the results of the first round simulation, eight alternatives that theoretically achieve flexibility to flood defence and urban ventilation were produced on the concept level. The second sub-research question (How can the adjustable dike structure optimize the flow of a cool breeze?) was stepwise discussed. Comparing the second simulation outcomes with the previous provided a clue to select the alternatives that outperform the others in terms of ventilation efficiency to get into the next design loop.

In the second design loop: structural stability, the four selected alternatives were further developed into the constructive level by designing their technical sections based on the topography and the flood defence standard of the testbed. Some similar existing practices were referred to estimate and improve the stability, then the most promising structures were selected. So far the second sub-research question was finally answered.

SRQ 3

The third sub-research question (What is the potential of adjustable dike structures to create places providing social functions?) was answered through the three parallel landscape design based on the alternative structures that perform outstandingly in ventilation efficiency and structural stability. In this exploratory site design, what social multifunctions can be integrated into the adjustable dike structures according to its relationship with the adjacent landscape and the neighbourhoods were discussed here. The three well-developed site design and the social functions they serve would be the answer to SRQ 3.

A graphic overview (Figure 1.6.1) of the research structure is shown on the next page. In the flow chart, what methods have been used and which research question has been addressed are demonstrated.

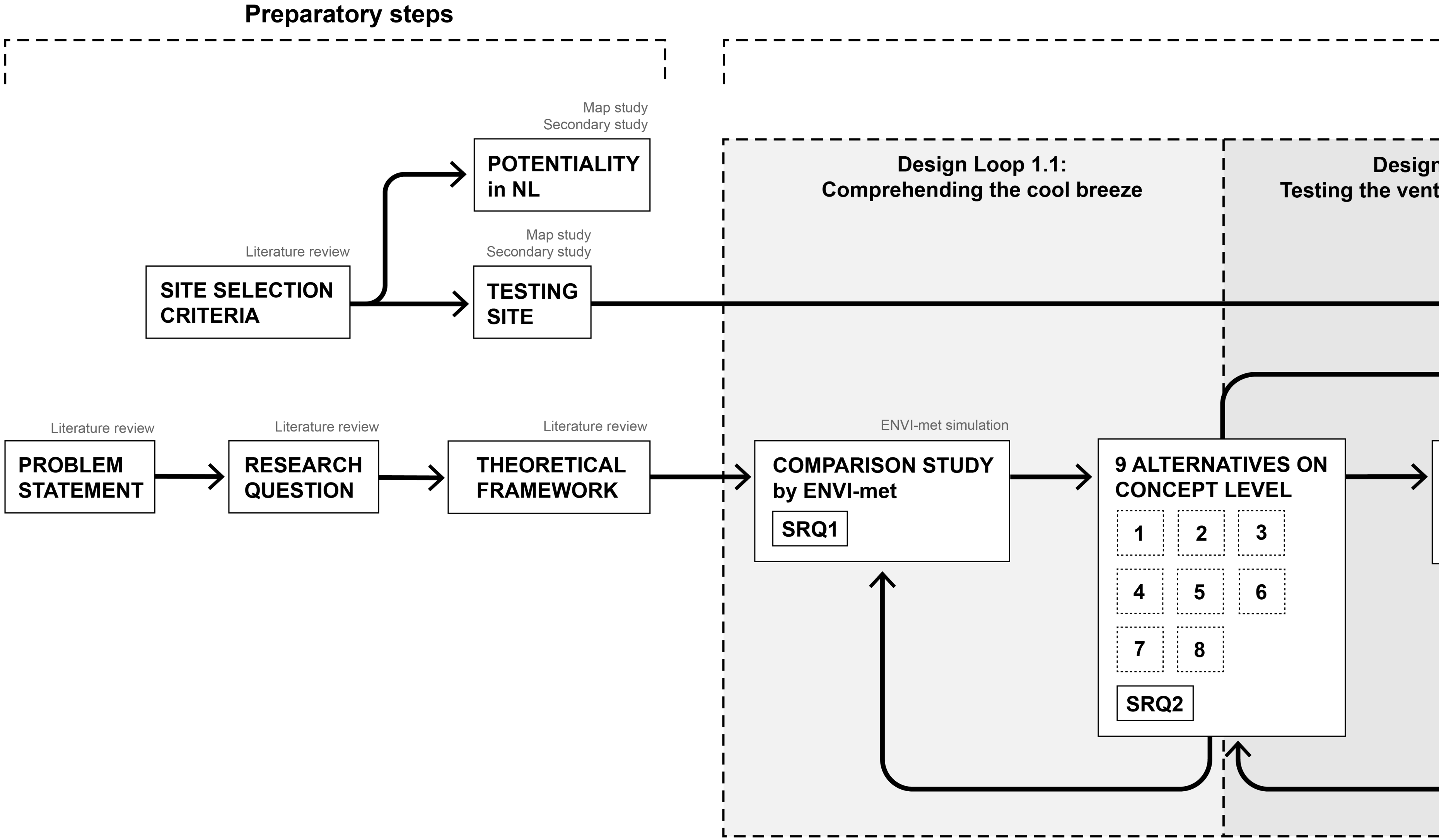
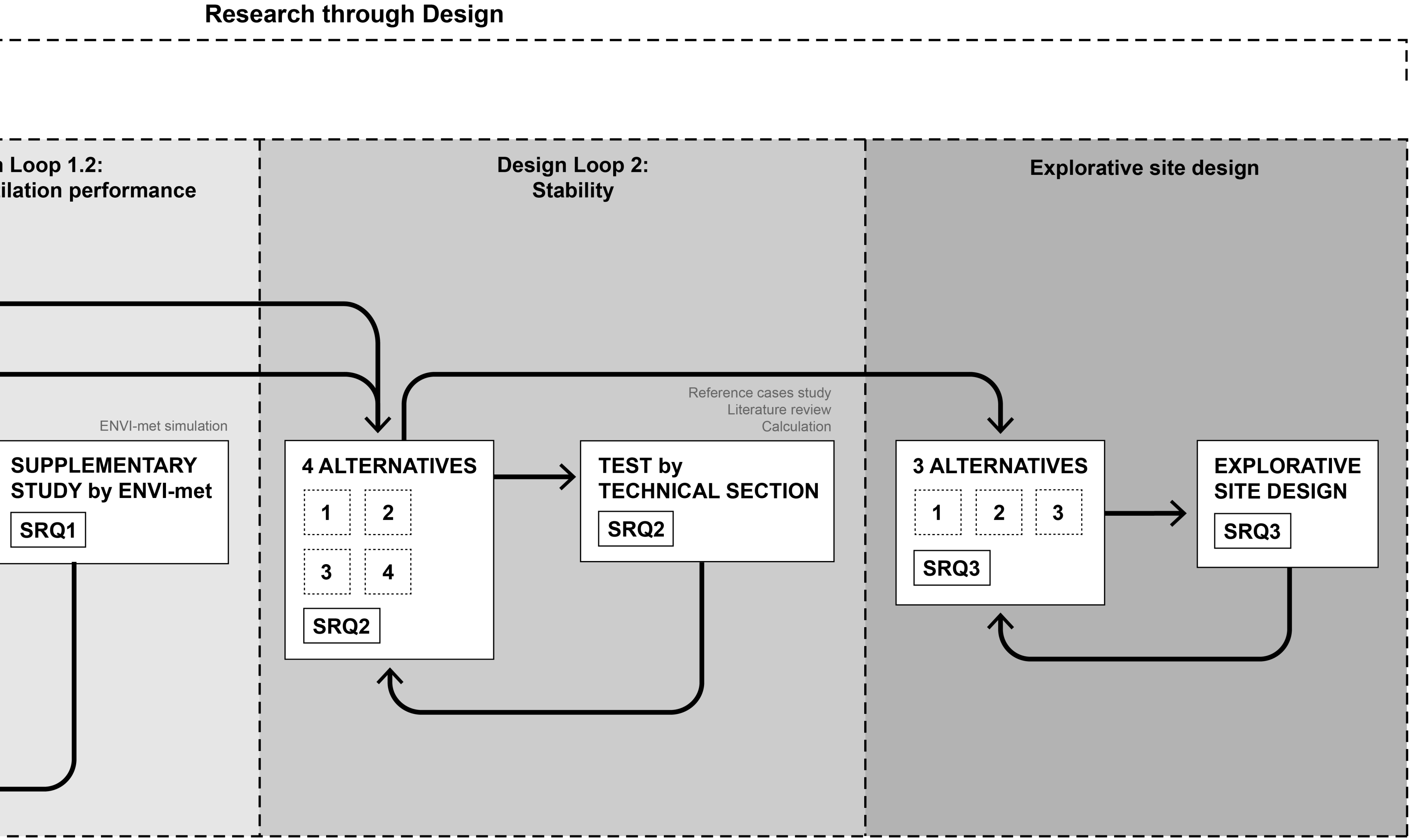


Figure 1.6.1 The research structure


Research through Design
n Loop 1.2:
ilation performance
Design Loop 2:
Stability
Explorative site design
ENVI-met simulation
SUPPLEMENTARY STUDY by ENVI-met
SRQ1
4 ALTERNATIVES
1
2
3
4
SRQ2
Reference cases study
Literature review
Calculation
TEST by TECHNICAL SECTION
SRQ2
3 ALTERNATIVES
1
2
3
SRQ3
EXPLORATIVE SITE DESIGN
SRQ3

2 Theoretical framework

2.1 Introduction

This thesis was addressed on the interface between flood defence, urban ventilation, and shared social functions. In this chapter, the background knowledge of urban ventilation, functions of floodplain and multifunctional flood defence are elaborated. Based on the theoretical framework, I developed the design hypothesis.

2.2 Urban ventilation

UHI mitigation

Mitigating the urban heat island effect is a big challenge in climate-responsive design (Lenzholzer & Brown, 2013). Reducing the UHI effect in cities with the heat problem has many benefits, including improving liveability, upgrading the quality of outdoor space, decreasing energy consumption for artificial cooling, decreasing biological emissions and reducing the mortality that is relevant to heatwaves (Erell, Dennis., Williamson & Pearlmutter, 2011).

One of the efficient mitigation measures is to invite wind to come into the area with heat problems (Lenzholzer, 2015). There are many ways to achieve urban ventilation based on the topography. The three most common urban ventilation resources are the sea & river breeze, the valley breeze and the urban wind between warm and cold climatopes. The river breeze is different from the sea breeze, but usually, they are not desired because it brings warm air into the city in the evening and the night (Zhong, Leone, & Takle, 1991). In the more specific description, it is called the land breeze during the day and the sea/river breeze in the night. The valley wind system and the thermal-driven wind system are actually very valuable to urban ventilation. In the more specific description, valley wind is called the mountain breeze during the day and the valley breeze in the night. In order to facilitate the valley breeze, both the upper land and the downhill axis should be kept open. For this study, the thermal-driven breeze between warm and cold climatopes is more relevant. In order to make use of this type of breeze, the interface between warm and cold climatopes should be kept open and as long as possible.

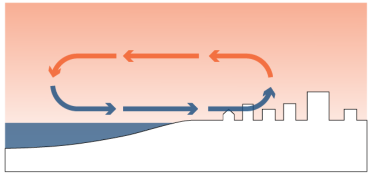


Figure 2.2.1
Sea/river breeze during the daytime
(Based on Indiana University, 2007)

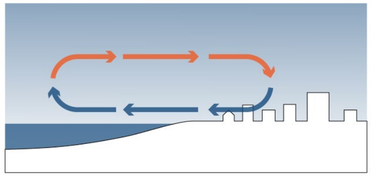


Figure 2.2.2
Land breeze during the night
(Based on Indiana University, 2007)

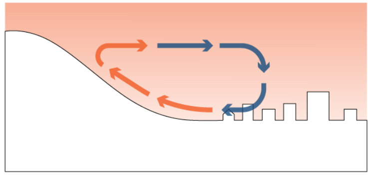


Figure 2.2.3
Mountain breeze during the daytime
(Based on Rafferty, n.d.)

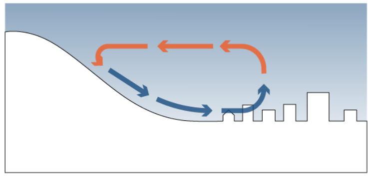


Figure 2.2.4
Valley breeze during the night
(Based on Rafferty, n.d.)

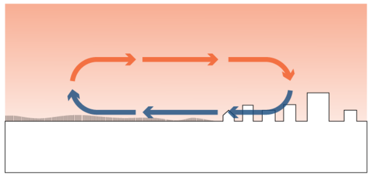


Figure 2.2.5
Thermal-driven wind during the daytime

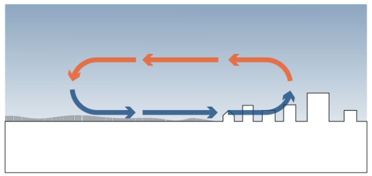


Figure 2.2.6
Thermal-driven wind during the night

Thermal-driven wind

The local urban wind between climatopes is also called the intra-urban thermal breeze, and the IUTB in short. It is a weak thermal-driven flow on the surface caused by the rising of warm air on the urban climatope, so that cold air from surroundings gets sucked in. It appears in the calm, clear sky summer night when UHI effect is strong. The cool airflow is around 0.3m/s to 0.5m/s (Erell, Dennis., Williamson & Pearlmutter, 2011). The calm night refers to the night without regional scale wind above 1.5m/s. The cooling effect of the breeze from green space has been discussed in many researches over the world. The outcomes strongly depend on the landscape and the climatological context, because the IUTB is a complex phenomenon including the exchange of heat between different pressure zones in different scales (Krautheim, Pasel, Pfeiffer, & Schultz-Granberg, 2014). For example, the research in Singapore indicates the cooling range will not excess 400m from the border when the green area excess 400m diameter (Yu & Hien, 2006). However, another study in Tokyo finds that averagely 200m from the park boundary is the maximum cooling range in the calm summer night, and the cooling effect is 39W/m (Sugawara, et al., 2016). Besides, 250m away from the park border has been mentioned as the average (Erell, Dennis., Williamson & Pearlmutter, 2011).

In order to make use of the temperature difference between climatopes, the airflow pattern needs to be studied for the specific site and across time. This metrology effect has many names: the IUTB, the thermal-driven breeze, the green landscape/park breeze, the urban wind, the cold airflow and etc. In this research, I unified to call it the 'Cool Breeze'.

As mentioned above, the cool breeze is slow and vulnerable. The frictional obstruction of ground to the cool breeze is small when the terrain is flat and smooth. But, any topologies, buildings and vegetation can obstruct the ground flow (Erell, Dennis., Williamson & Pearlmutter, 2011) That is why 'the area where cool air originates from and the ventilation direction should be kept open' (Lenzholzer, 2015).

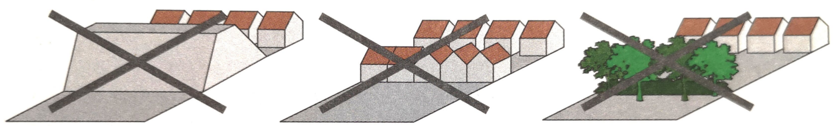


Figure 2.2.7 The ventilation channel should be kept open (Lenzholzer, 2015)

2.3 The role of the floodplains

Flood control

In Dutch, the floodplain is called 'uiterwaard', which means outer land (Pleijster, et al., 2014). At many places along the main river system in the Netherlands, two dike lines can be found. The lower one, which is closer to the permanent water, is called the summer dike, and the taller and more inland one is called the winter dike. When the winter dike operates, the floodplain is functioning as a part of the riverbed to improve flow capacity and spare flood (Pleijster, et al., 2014). Due to their location, summer dikes are not considered to be a threat to the cool air exchange.

The wide floodplain has many benefits. It increases flood conveyance capacity, which helps to river discharge. Also, it has been proven that the floodplain is able to decrease the damage of flood and reduce the chance

Figure 2.3.1 The floodplain of Wageningen ("Tichelgaten in de Wageningse uiterwaarden - Wiki Wageningen", 2020)

of dike failure. Moreover, widening river bed might lower the future flood level. This hasn't been proved by practice, but possibly more floodplains will make the river system more robust (Klijn, Asselman, & Wagenaar, 2018).

By 2018, the Dutch Room for the River project has been accomplished. The nine different approaches of making room for the rivers have been applied in more than thirty locations along the river Rhine, Waal, Maas and Ijssel: lowering the floodplain, deepening the summer bed, water-retaining, dike relocation, lowering perpendicular groynes or building attracting groynes, highwater channel, depoldering, removing obstacles, and strengthening dike ("Ruimte voor de Rivier", 2019). The completion of Room for River project implies the role of floodplains has been given more attention in the field of water management. It is believed that more preserved floodplains will be seen in the future. From the urban climate perspective, the function of those floodplains near the urban area is not only flood control, but also cool air production.

Cool climatope

The topography of floodplains is normally flat with very limited hard paving, a small number of willow trees, reeds, creeks and sometimes farmhouses. Due to its openness, solar radiation partly reflects back to sky during the day, and longwave radiation can easily emit to the air without obstructing during the night. Besides, evaporation of plants and transpiration on the open soil also contribute to the dropping in air temperature. Together they are the reasons why floodplains cool down very fast after stopping receiving solar radiation (Lenzholzer, 2015). Therefore, the floodplain is considered to belong to the green and open landscape climatope. Amongst the eleven types of climatopes, the open landscape climatope is called the 'cool air producer' (Lenzholzer, 2015).

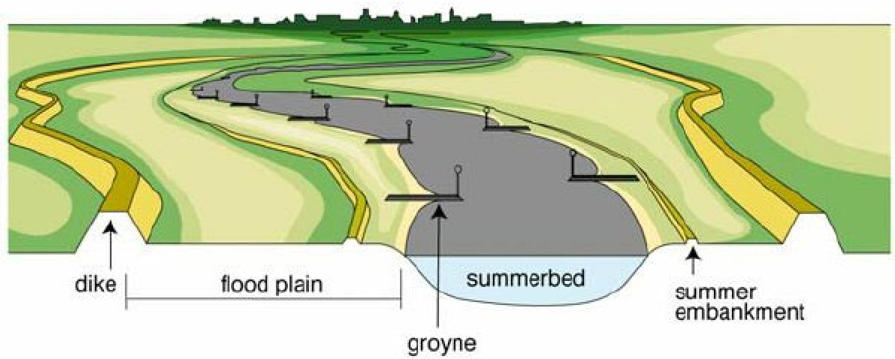


Figure 2.3.2 The typical cross-section of a floodplain (Douben, Silva, Klopstra, & Kok, 2007)

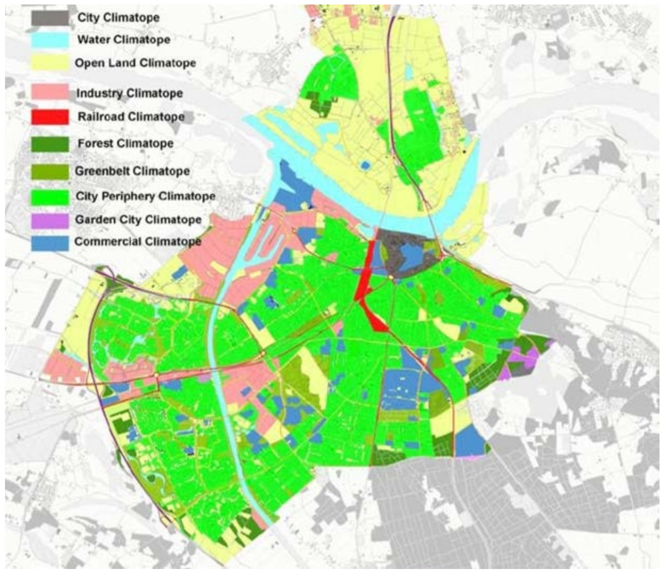


Figure 2.3.3 The climatope map of Nijmegen (Lenzholzer & Brown, 2013)

2.4 Multifunctional flood defence

Multifunctional flood defence is a combination of flood defence and other functions, such as transport, agriculture, recreation, residential, eco-service and renewable energy, on limited spaces (Kok, 2017). The combining becomes necessary not only because of climate change, but also the rising residential and economical demands within the dike ring where densely built-up areas are already squeezing the public space. One of the benefits of multifunctional flood defence is their economic value. Some of the multifunction might bring income which helps to finance the construction and maintenance of the defence structure (Kok, 2017). For example, integrating the parking garage, retail and other activity spaces are profitable. In brief, multifunction has many benefits, but combining functions is challenging each one of them, especially the primary function (Kothuis, & Kok, 2017). Importantly, the integration of any multifunctions should be based on the guarantee of flood defence (Vrijling, 2017).

Flood defence

Dutch people have a long history of competing with water. Various flood defence measures have been developed (Ven, 2004). Dutch dikes can be generally divided into the four categories: the sea dike, the upriver dike, the lower river dike, and the polder dike, which consists of 43 essentially different types. The height of them ranges from around 10m (the sea dike) to less than 1m (the summer dike/sleeper dike). The height of river dikes depends on the rate of river flow, and in some part of the river Waal and Rhine, it can reach approximate 5m (Pleijster, et al., 2014).

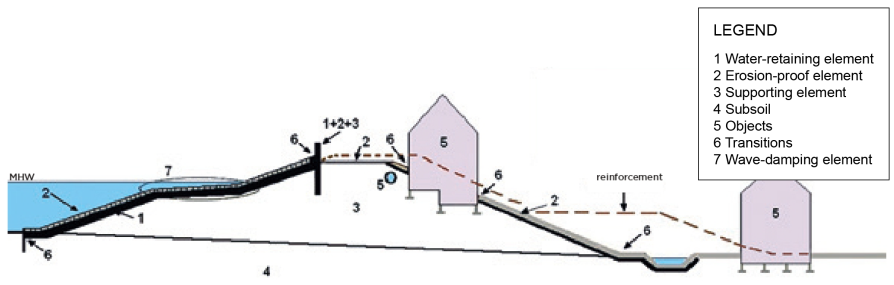


Figure 2.4.1 Flood defence structural elements. (Voorendt, 2017)

Flood defence on the basic level is to make a barrier of a certain height ("NYC: The BIG U | Rebuild By Design", 2014). To be elaborative, flood defence needs to have the capabilities from three aspects: (1) retaining water, (2) transferring the load to the earth, and (3) resisting the transferred load. In order to retain water, the structure needs to prevent overflow by providing enough height and a solid support and enough width to prevent the flow under and around the defence. To transfer the load to the ground, the structure needs to provide stability, strength and stiffness. Basically, the three capabilities are fulfilled by the seven types of structural elements: (1) water-retaining elements, (2) erosion-proof elements, (3) supporting elements, (4) subsoil, (5) objects, (6) transitions and (7) wave-damping elements (van Veelen, Voorendt, & van der Zwet, 2015).

The water-retaining element is usually a clay layer covering the sand core of the dike, or a defence wall in any forms. The erosion-proof element is a solid layer of bricks or concrete blocks on top of the clay layer to prevent erosion from waves. But it is not indispensable for every case. For large sea dikes, so-called 'dolosse' and 'tetrapods' are placed on the outer slope. In addition, grass on the slope and the asphalt road on the dike crest are also functioning as erosion-proof elements. The sand core and the subsoil are the third and the fourth structural elements. The fifth elements (objects) could be utilities, houses or any other integrated structures for multifunctions, but objects are not essential for the dike structure. The transition is the material that connects two elements, such as the curbstone between the asphalt road and the grass-covered slope. For the last, a part of the outer slope that is less steep is the wave-damping element. It aims to defuse the pressure on the dike body (Kothuis, & Kok, 2017).

Integration level of multifunctional flood defence

The integrity of multifunctional flood defence can be described into the three levels: (1) spatial integration, (2) structural integration and (3) functional integration (Veelen, Voorendt, & Zwet, 2015). Aside from the three levels of integration, the shared-use of a dike without any intervention on the structure is also common, such as grazing on the dike slope and recreation on the lawn. At the level of spatial integration, the structure for the secondary function is not part of the defence structure. Examples can be found frequently in the densely urbanized delta area. At the second level, the additional structure is part of the defence structure but not directly retaining water. To be regarded as functional integration, the multifunctional structure itself needs to be the water-retaining element at the same time (Veelen, Voorendt, & Zwet, 2017).

As the instruction to my alternative dike design, the ventilation purpose can only be achieved on the level of functional integration because the structure itself needs to be adjustable. Meanwhile, other social functions could be addressed on the level of structural integration and spatial integration, or just a shared-use of the defence structure.

Possible failure mechanism of multifunctional flood defence

After identifying the crucial elements of a successful flood defence structure and understanding in what ways the multifunction could be integrated, the nine potential failure mechanisms of multifunctional flood defence are gathered in this section. They are (1) erosion between the multifunctional element and the foundation, (2) leaking in between elements, (3) vibrations from objects that weaken the defence structure, (4) piping, (5) instability of the object, (6) insufficient strength of the object, (7) non-closure of gates, (8) overflow or overtopping of gates and (9) falling objects (Voorendt, 2017). It is worth to mention again any multifunctions should be based on the guarantee of flood defence function. Therefore, the above failure mechanisms should be carefully prevented in the later design.

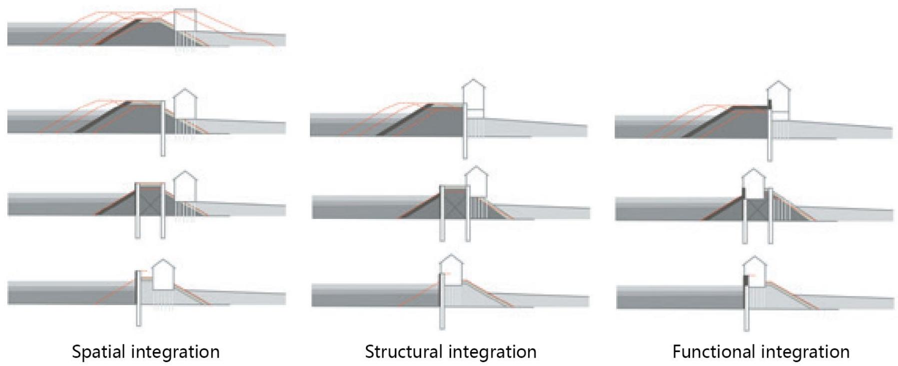


Figure 2.4.2 The level of multifunctionality and integration of multifunctional flood defence (Veelen, Voorendt, & Zwet, 2017)

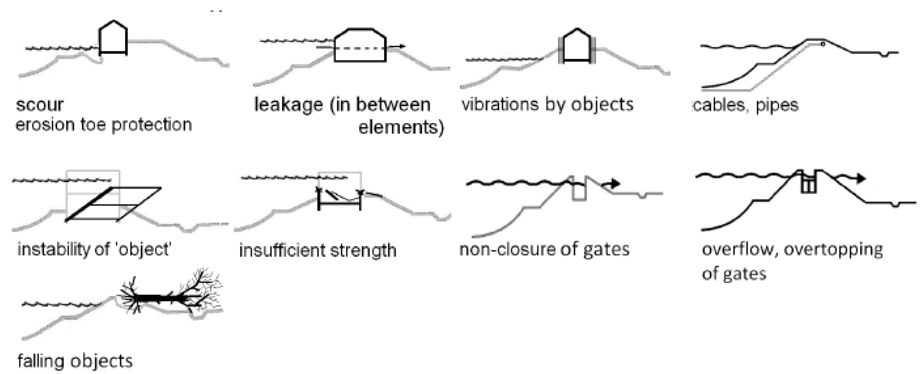


Figure 2.4.3 The overview of possible multifunctional flood defence failure mechanisms (Voorendt, 2017)

Practice of multifunctional flood defence

The multifunctional flood defence has been explored in many study and practice. The most successful and widely applied example of multifunctional flood defence is the road on the dike crest. The traffic activity has no negative influence on the defence function, or the other way around. Moreover, the dike and the road are not only co-existing but also synergetic to each other, because the asphalt surface of the road sometimes functions as the erosion proof element to the overtopping wave (Kok, 2017).

The projects, such as the multifunctional sea dike at Katwijk aan Zee and the Dakpark at Rotterdam are also successful. The multifunctional sea dike at Katwijk aan Zee perfectly integrates the defence element and the parking garage into the sand dune landscape, which achieves multifunctionality at the same time creates the unique landscape experience. The Dakpark integrates the interest of different stakeholders by making multifunctional flood defence on the limited space (Raaphorst, 2017).

In this research, urban ventilation was seen as the prioritized multifunction. According to the current understanding of cool air exchange between the floodplain and the urban area, ventilation can only be accomplished by operating on the level of functional integration. Next to that, the shared traffic function should be preserved in my design in order to make the alternatives generically applicable to replace the existing dike. Other social functions are better to be addressed on the integration level of shared-use and spatial integration in order to have less impact on the flood defence function. On top of those, the possible failure mechanisms of multifunctional flood defence should be avoided in the future design.

Figure 2.4.4 A dike road

Figure 2.4.5
The multifunctional sea dike, Katwijk aan Zee
("Katwijk aan Zee", 2015)

Figure 2.4.6
The Dakpark, Rotterdam
("Dakpark Rotterdam - Buro Sant en Co", 2020)

2.5 Conclusion from theory and design hypothesis

As elaborated in the preceding parts of the theoretical framework, this is an interdisciplinary study between flood defence and urban ventilation. From the perspective of climate responsive design, the climatic problem and resource should be analysed on the time-based dimension. On the year-round scale, the asynchronism of flood and heatwave has been identified. The seasonally different demand for the dike ensure the possibility of designing an adjustable flood defence alternative.

The daily weather information from 1956 until today collected from over 400 weather stations can be downloaded from the KNMI website. By overlapping the three groups of crucial weather data: (1) the daily mean temperature, (2) the water level, and (3) the daily precipitation on a year-round timeline, the general pattern was found (Figure 2.5.1). Extreme weather, such as heavy storms and floods, is likely to happen in the period from autumn to spring (from October to March). In this period, the defence function is required, but urban

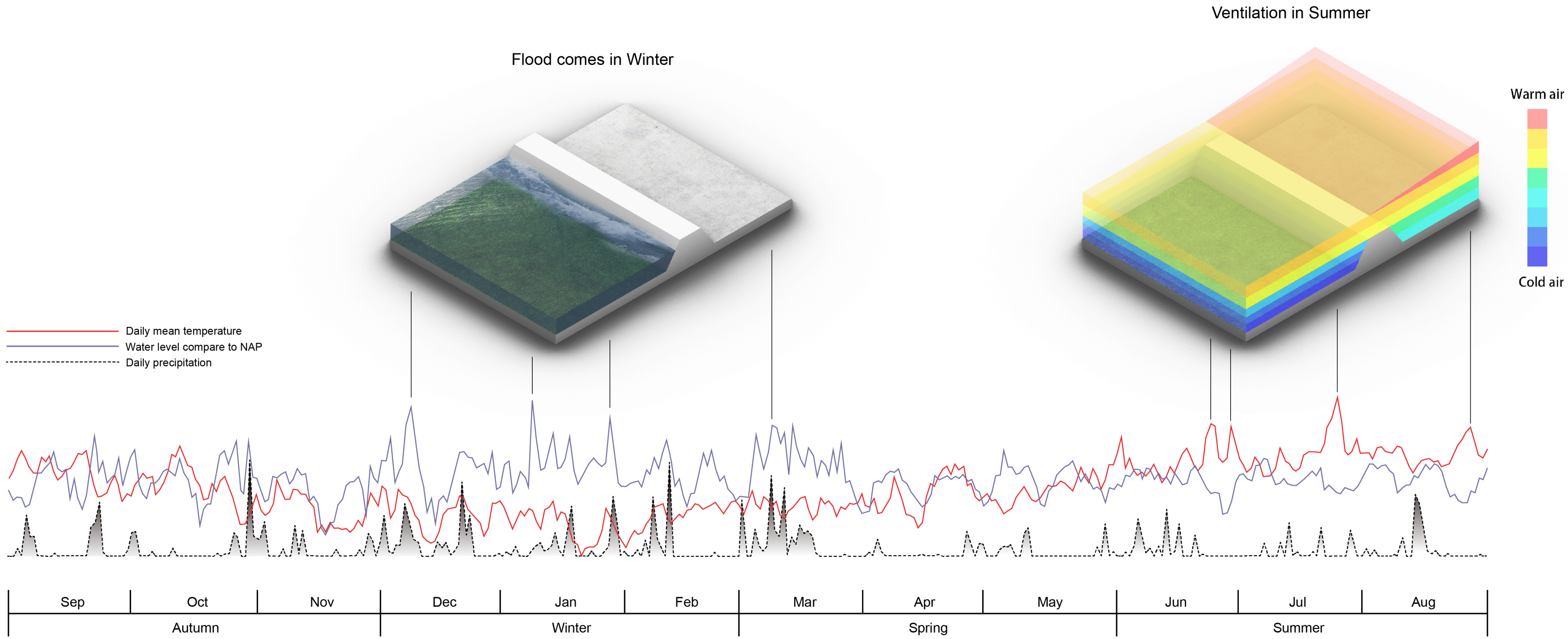


Figure 2.5.1 Seasonal demands indicated by overlapping the weather data (Based on "KNMI - Daggegevens van het weer in Nederland", 2020)

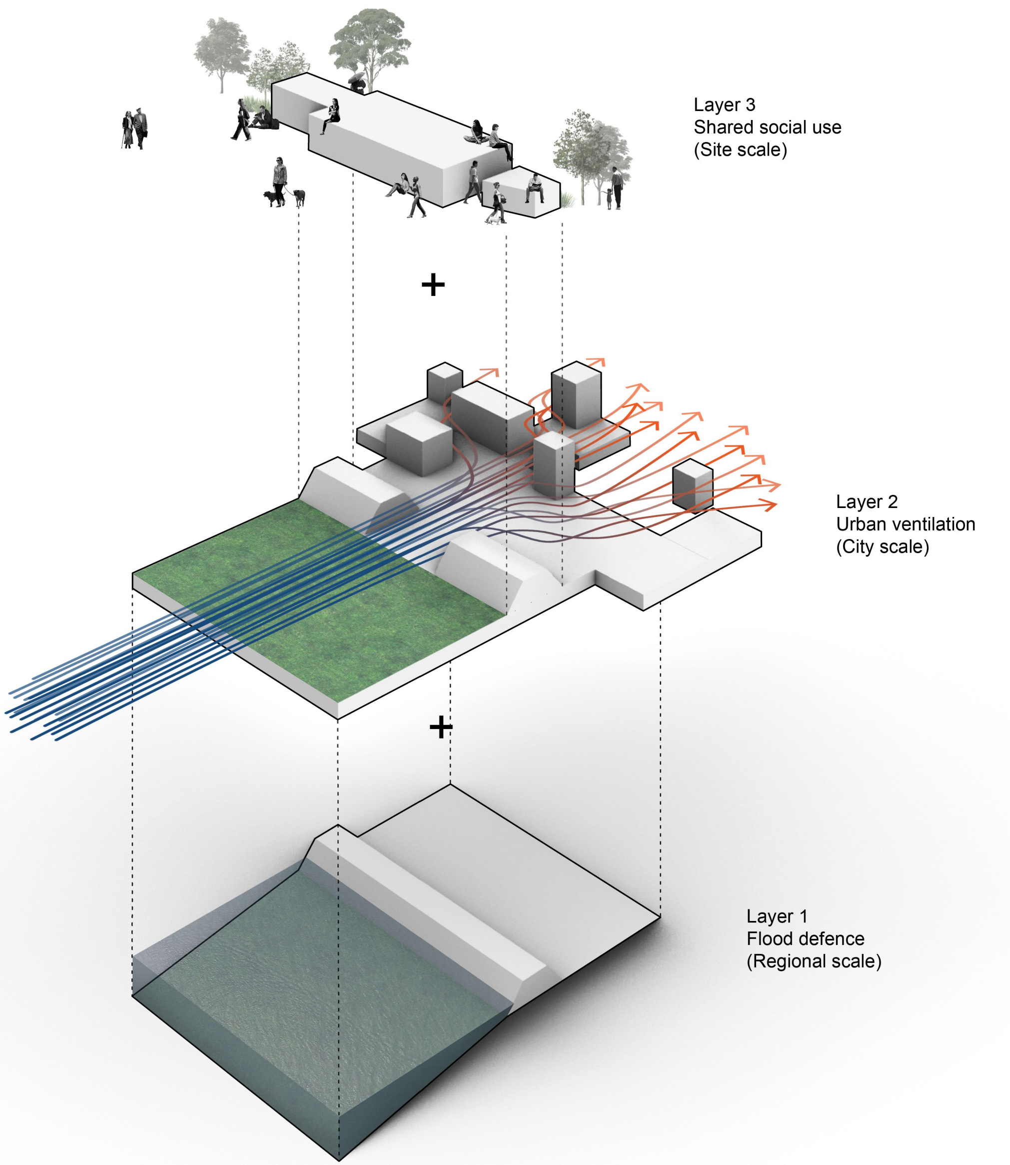


Figure 2.5.2 The design hypothesis of layered use of the flood defence space

ventilation is definitely not demanded. Conversely, in the summer (from June to August), ventilation is expected when the heatwave appears, but very little heavy rainfalls happen.

The asynchronism of demand makes the seasonal adjustable flood defence structure possible, which further leads to the design hypothesis: **Layered use of the flood defence space**. The function on the basic layer is flood protection that should be guaranteed in any alternatives. The flood defence function has the impact on the regional scale. Above that, urban ventilation is on the second layer which has the impact on the city scale.

On top of flood defence and urban ventilation, the new structure might provide a possibility for other multifunctions on the third layer of spatial usage. Generally, the function on each layer is related to one of the sub-research questions. By demonstrating the design hypothesis, the research questions would be answered.

3 Test bed identification

3.1 Introduction

According to the theoretical framework, the airflow pattern and the cooling effect of green & open space are strongly related to the topography, the microclimate context and the neighbourhood fabric (Erell, Dennis., Williamson & Pearlmutter, 2011). Therefore, in order to answer the SRQ1, the cool breeze and other relevant microclimate process were studied site-specifically by running the ENVI-met simulations for the testbed.

After that, in order to answer SRQ2, the existing heat problems and the flood protection standard of the testbed were important for further evaluation of the ventilation efficiency and the structural stability of the flood defence alternatives.

In the end, the testbed would be used in the site design phase to test the applicability of the new adjustable flood defence structures. Moreover, the preferred shared social function is depending on the demography of the nearby communities (Anvarifar, Zevenbergen, Thissen, & Islam, 2016). The alternative design should not be done without the context. In a word, the testbed was necessary for both Design Loop 1, 2 and the explorative site design. This chapter elaborates how the testbed was selected.

3.2 Selection criteria

The testbed selection criteria were developed based on the current understanding of a cool breeze. Basically, the testbed needs to have the three crucial factors: (1) the 'resource' -- the floodplain, (2) the 'problem' -- the dike, and (3) the 'demand' -- the residential area with heat problems.

Firstly, The cool breeze only appears when the urban heat island effect is strong (Erell, Dennis., Williamson & Pearlmutter, 2011). So, sites with the strong UHI and heat problems are more suitable to be the testbed. Secondly, the wider floodplain with a big sky view factor is likely to produce more cool air during the night. Besides, the cooling range of an open green space varies from 200m (Sugawara, et al., 2016) to 400m (Yu & Hien, 2006). And a bigger temperature difference is likely to provoke a stronger cool breeze. So the sites where the floodplain is close to heat problems are prefered. After that, the testbed should be a place where the terrain is flat, because if the green area is in a low position, the cold heavy air is hard to get out, which restricts its cooling effect (Lenzholzer, 2015). In the end, because the cool breeze usually happens in the night, it is unwise to target the land-use of commerce, offices, warehouses or industry in which very few people stay during the night. Therefore, the site where residential areas are behind the dike is more meaningful in this research.

Hence, the criteria was formulated:

1. **Urban heat problems**
2. **A floodplain**
3. **A tall dike**
4. **The floodplain is close to heat problems**
5. **A flat terrain**
6. **Cooling demand**

3.3 Potential sites in the Netherlands

The first step was to identify as many as possible potential sites in the Netherlands. The urban heat map (Figure 3.3.1) indicates which cities have the strongest UHI effect and what are the temperature patterns in those cities. As the urban heat map indicates, obviously those big cities, such as Rotterdam, Amsterdam and Den Haag have the stronger UHI effect. Specifically, in the city of Rotterdam, the UHI intensity can be up to 10°C. Even the suburbias of Rotterdam are about 2°C warmer than the adjacent arable fields and the nature areas (Klok, et al., 2014). The dike map (Figure 3.3.3) and the topology map together indicate where and how tall the dikes are. 22,500 km of dikes locate at the coastline and on two sides of the Rhine, Maas, Waal and Ijssel river, excluding the part nearby the Veluwe region where the terrain is higher on the northside of the Rhine, and some parts along the Maas in the relatively 'montanic' region. In the end, the national water system map (Figure 3.3.2) shows where the floodplains are. As a byproduct of the site selection activity, the prospect of conducting seasonally adjustable flood defence in the Dutch context is predictable. By overlapping these three maps, 32 potential sites in the Netherlands were identified.

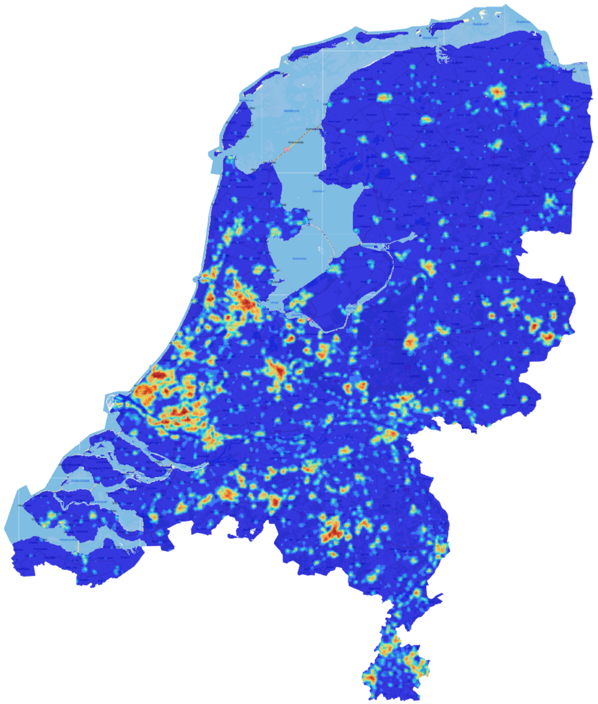


Figure 3.3.1 The urban heat map of the Netherlands ("Climate Impact Atlas - Klimaateffectatlas", 2020)

Figure 3.3.2 The national water system map of the Netherlands

Figure 3.3.3 The dike map of the Netherlands (Pleijster, et al., 2014)

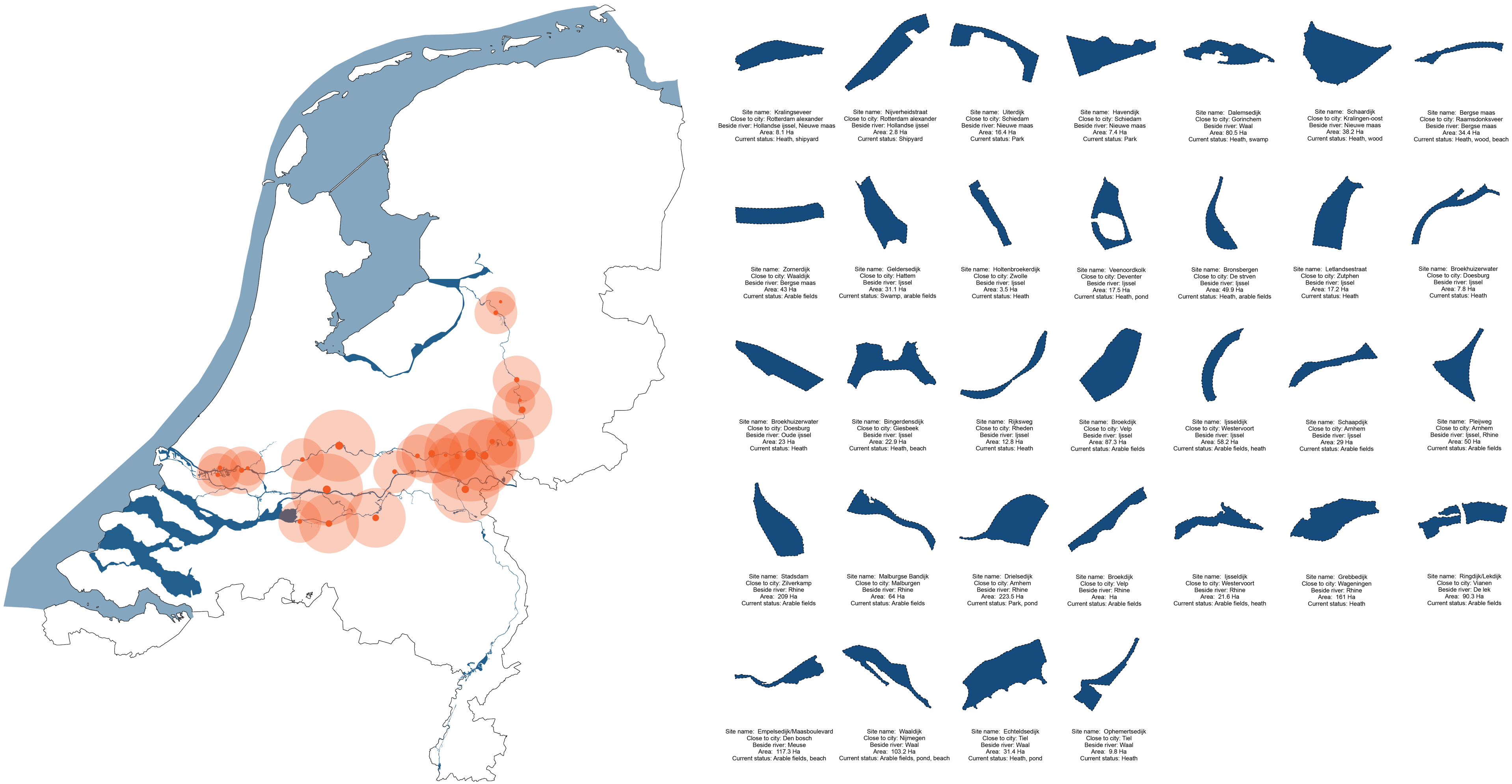


Figure 3.3.4 Overview of potential sites in the Netherlands

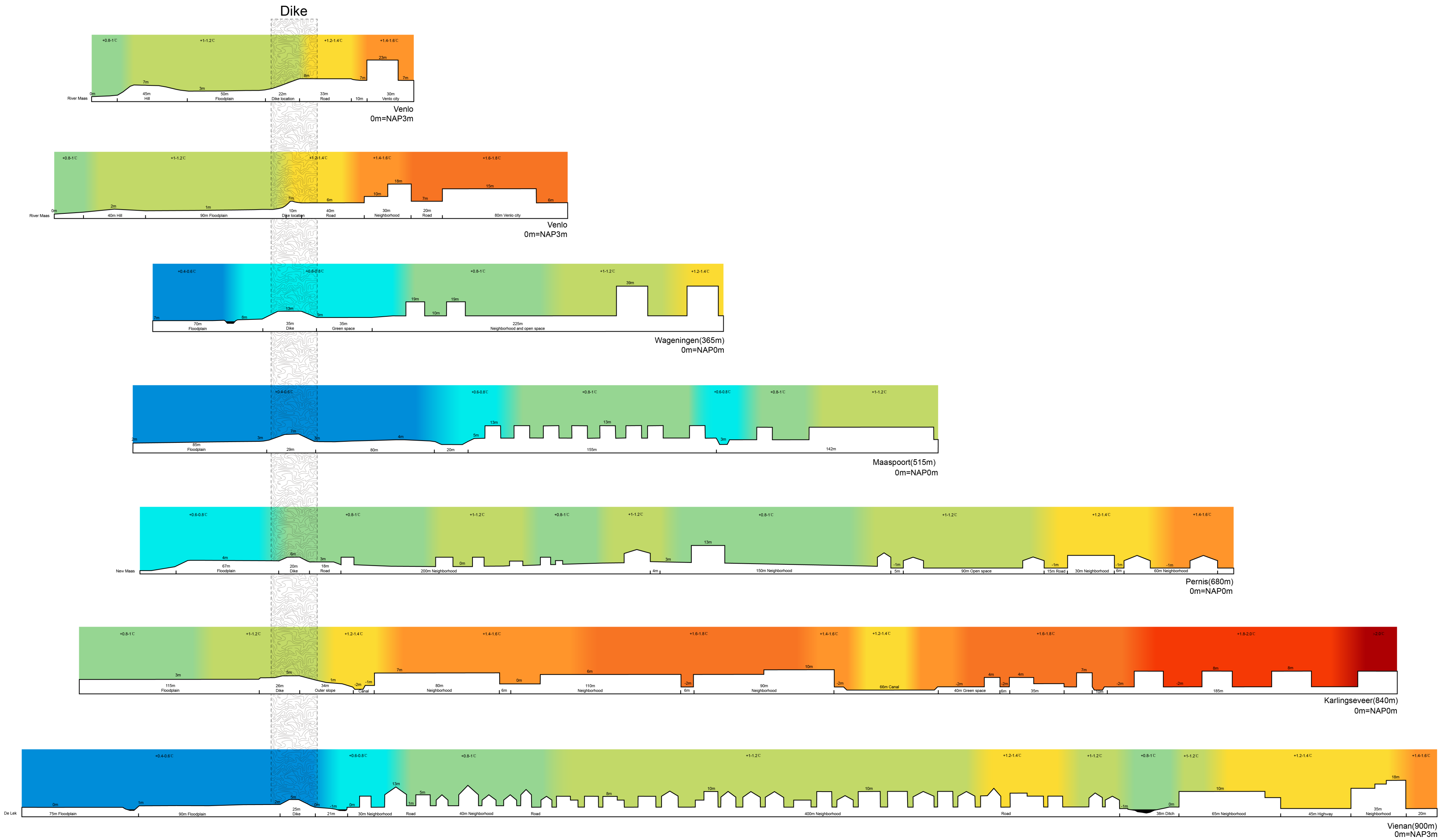


Figure 3.3.5 Overview of sections of potential sites' temperature gradient and topography (Based on "Climate Impact Atlas - Klimaateffectatlas", 2020)

The second step is to choose the most suitable site amongst them. I overlapped the temperature gradient and the urban topography of each potential site. The site that has the steepest temperature rise, and where the urban heat problem is the closest to the floodplain, is likely to provoke the strongest cool breeze, which makes it suitable to be the testbed. According to the analysis, the IJsseldijk and nearby neighbourhoods were considered to be suitable. On that site, from the dike towards the neighbourhoods, the air temperature rises 1°C on the distance of 180m. The terrain on two sides of the dike is not completely equal, but higher on the side of the floodplain and lower on the inner side, which should not be problematic to the breeze.

	Site 1: Venlo Maas	Site 2: Vianen De Lek	Site 3: Pernis New Maas	Site 4: Kralingseveer New Maas	Site 5: Maaspoort Maas	Site 6: Wageningen Rhine	Site 7: Schiedam Zuid New Maas	Site 8: Tiel Waal	Site 9: Waalwijk Bergsche maas
Urban heat problem	✓	✓	✓	✓	✓	✓	✓	✓	✓
Floodplain	140m	300m	60m	140m	160m	860m	170m	325m	225m
Dike height	3.5m/0m	5.1m/4.7m	1.9m/2.7m	1.8m/5.5m	4.5m/4.4m	5.5m/4.1m	1.7m/1.5m	6m/6m	5m/5.3m
Distance to heat problem(0.8℃)	/	115m	485m	180m	/	250m	400m	380m	370m
Water infrastructure	✓	✓	✗	✗	✗	✗	✓	✓	✗
Flat terrain	✗	✓	✓	✗	✓	✗	✓	✓	✓
Cooling demand	✓ (Residential)	✓ (Residential)	✓ (Residential)	✓ (Residential)	✓ (Residential)	✓ (Commercial)	✓ (Residential)	✓ (Residential)	✗ (Industrial)

Figure 3.3.6 Information of potential testbed regarding the selection criteria

3.4 Case

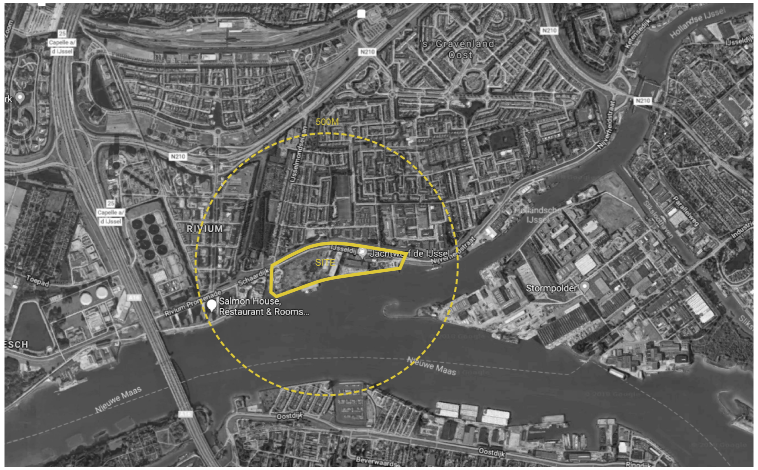


Figure 3.4.1 The satellite image of testbed and the theoretical cooling range

Figure 3.4.2 Kralingseveer in 1918 ("Geschiedenis – Laankerk.nl", 2017)

Figure 3.4.3 The section of Kralingseveer's temperature gradient and topography

Description

The neighbourhood Kralingseveer protected by Ijsseldijk is adjacent to an unused floodplain of 160m on the south-north and 700m on the east-west. Amongst all potential sites, Kralingseveer has the most serious heat problems and the most intense temperature increase from the floodplain. Next to that, the dike is extremely tall amongst river dikes. It is 6.5m to the inner ground and 5m to the outer floodplain, which means the floodplain is a bit higher than the neighbourhoods. This terrain can be seen as an advantage to future ventilation. According to the site selection criteria, the area including the floodplain, Ijsseldijk, Kralingseveer and the adjacent neighbourhoods was selected to be the testbed.

Kralingseveer was annexed by Rotterdam in 1941 and is now a small neighbourhood in the Prince Alexander district in the east of the municipality of Rotterdam. To be specific, the neighbourhood of Kralingseveer is a typical Dutch neighbourhood built after WWII, from 1945 to 1960. The name implies it was the ferry from Kralingen to IJsselmonde. The old community was built on Schielands Hoge Zeedijk, which almost broke through during the flood of 1953. In 1955, those old village houses were demolished for the dike reinforcement. Most of the houses we see nowaday were built after that. Kralingseveer is a densely residential neighbourhood with 1655 dwellers ("Geschiedenis – Laankerk.nl", 2017).

The site is on the border of three municipalities (Figure 3.4.5): (1) Rotterdam Municipality, (2) Capelle aan den IJssel Municipality and (3) Krimpen aan den IJssel Municipality. The floodplain is divided into two parts by the municipality borders. The closest neighbourhood to the floodplain is Kralingseveer, and it is located in the Rotterdam municipality, but the rest of adjacent neighbourhoods belong to the municipality of Capelle aan den IJssel. Only the river is in the border of Krimpen aan den IJssel municipality.

Site analysis

The information, including the location of the original dike, vegetations that may influence the ventilation, the status of the floodplain and other green spaces, the heat stress areas, the current road system and the land-use within the dike were gathered and visualized. This information helped me to make the decision of where the most efficient and feasible openings are.

Firstly, the crest of IJsseldijk has been used as a double-lane car road with heavy traffic. Cars can get off the dike from the two exits towards the neighbourhoods. The road network should be kept intact in the future design. Along the car road, the cycle path is located on halfway up to the inner slope of IJsseldijk. The current trees are rather isolated, which doesn't formulate obstacles between the floodplain and those neighbourhoods.

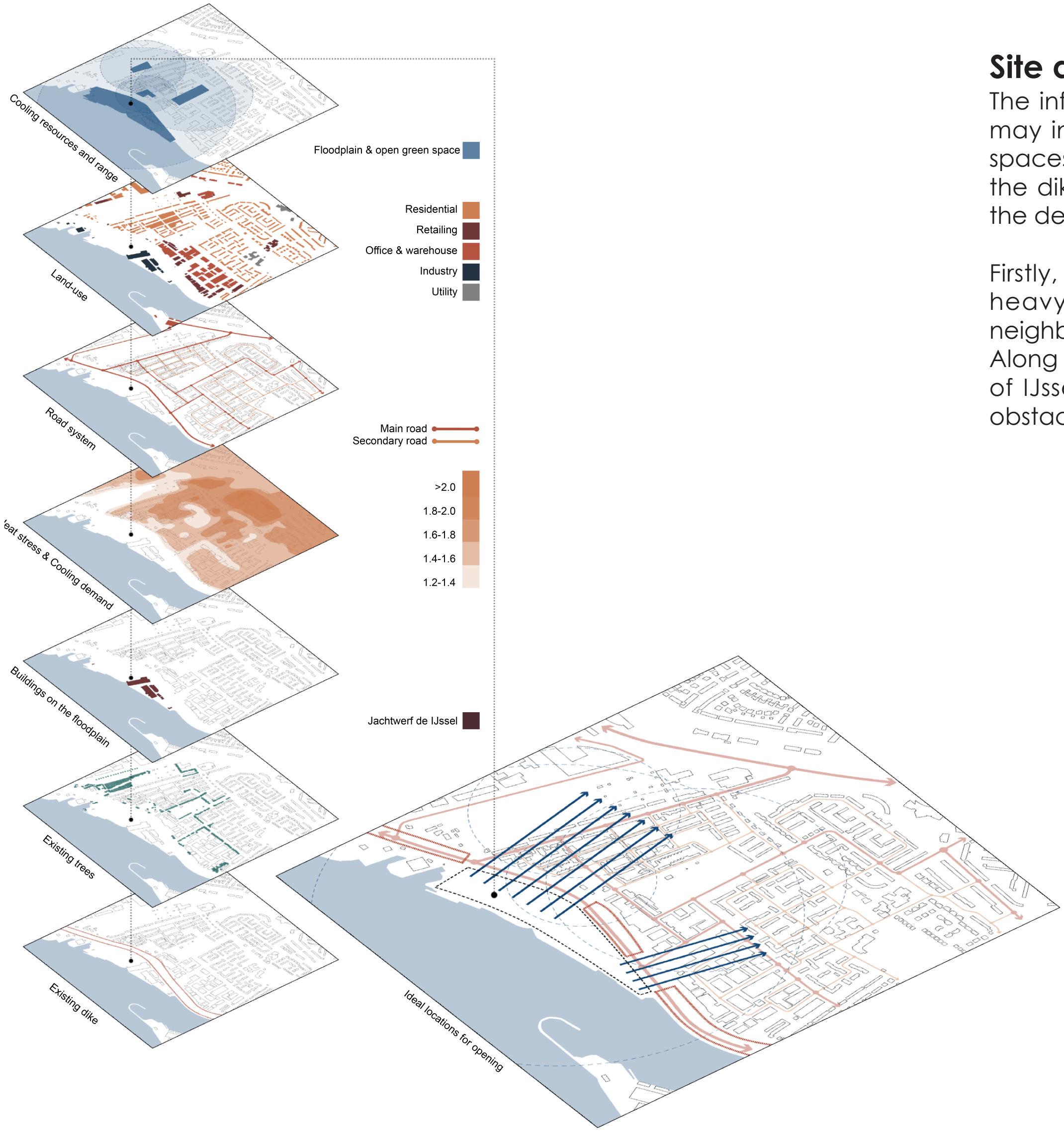


Figure 3.4.4 Overview of the site analysis: location of Ijsseldijk, vegetation, floodplain status, heat stress, existing road system, land-use, cooling range, and proposed location to be open in the dike

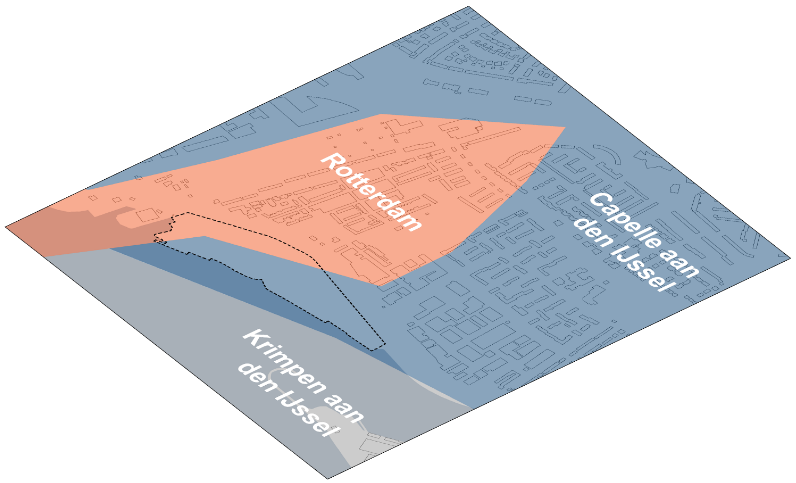
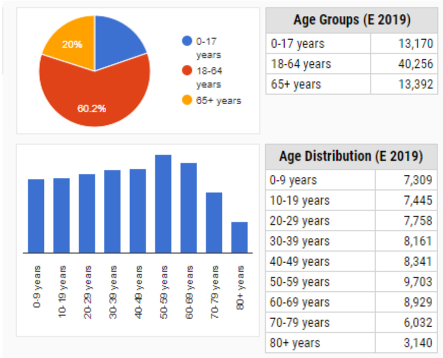


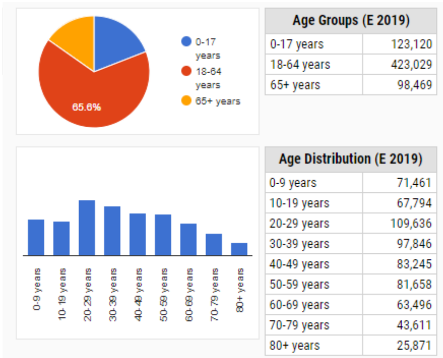
Figure 3.4.5 Tri-border-area between Rotterdam Municipality, Capelle aan den IJssel Municipality and Krimpen aan den IJssel Municipality ("Zuid-Holland (Province, Netherlands) - Population Statistics, Charts, Map and Location", 2020)



Age Groups (E 2019)	
0-17 years	13,170
18-64 years	40,256
65+ years	13,392

Age Distribution (E 2019)	
0-9 years	7,309
10-19 years	7,445
20-29 years	7,758
30-39 years	8,161
40-49 years	8,341
50-59 years	9,703
60-69 years	8,929
70-79 years	6,032
80+ years	3,140

Figure 3.4.6
Demographic information of Capelle aan den IJssel Municipality ("Capelle aan den IJssel (Municipality, Zuid-Holland, Netherlands) - Population Statistics, Charts, Map and Location", 2020)



Age Groups (E 2019)	
0-17 years	123,120
18-64 years	423,029
65+ years	98,469

Age Distribution (E 2019)	
0-9 years	71,461
10-19 years	67,794
20-29 years	109,636
30-39 years	97,846
40-49 years	83,245
50-59 years	81,658
60-69 years	63,496
70-79 years	43,611
80+ years	25,871

Figure 3.4.7
Demography information of Rotterdam municipality ("Rotterdam (Municipality, Zuid-Holland, Netherlands) - Population Statistics, Charts, Map and Location", 2020)

Secondly, according to the predicted urban heat map from the 'klimaat effect atlas' website, the heat problems are more intense in the inland blocks. The strongest temperature increase appears in the neighbourhood near the Chopinstraat on the north side. Generally, the air temperature increases at the places where building density is high, such as those row houses near the west exit from the dike road, those high-rise apartments and the big-roof warehouses in the middle, and the streets near the east exit from the dike road. If the dike is replaced by an openable structure, these areas are most likely to benefit from the ventilation.

According to the land-use within the dike, those houses on the west side are all residential. And the first row of buildings on the east side is a mixing zone of warehouses, offices and retails. The residential area on the west side and behind the mixing zone should be the ventilation targets, because those are the places where people stay in the evening and overnight.

Besides, two more open green spaces are located between the residential zone on the west side and the mixing zone on the east side. In the future design, the ideal breach in the dike should face these open areas in order to have a longer ventilation channel.

Due to the unique location of the testbed, the demographic information about the target neighbourhoods is hard to be acquired. The demographic information of Capelle aan den IJssel Municipality was the main focus, complementing with the information of Rotterdam municipality, because most of the neighbourhoods are located in the Capelle aan den IJssel Municipality. Krimpen aan den IJssel was not paid attention to, since no property but water is there.

50-59 and 60-69 are two of the biggest age groups in Capelle aan den IJssel. The population of elderly people is 5% more than Rotterdam. Elderly people are one of the most sensitive group to heat stress. The demographic composition of the neighbourhoods, combining with the living condition: 60s houses without air-conditioner, makes the community vulnerable to climate change (Albers, et al., 2015). In conclusion, these neighbourhoods need cooling interventions more than elsewhere. Apart from the microclimate and thermal comfort, other social functions for the elderly people should also be considered in the explorative site design.

Figure 3.4.8 Ljsseldijk, view from the floodplain

Figure 3.4.9 The weedy floodplain

Figure 3.4.10 The car road on the dike

Figure 3.4.11 The bike path on the dike slope

Figure 3.4.12 The neighbourhoods

Figure 3.4.13 The neighbourhoods, view from the dike top

4 Research through design

4.1 ENVI-met simulation

4.1.1 Method

ENVI-met 4 was the microclimate simulation software I used to quantify and visualize the warm-cool air interaction between the floodplain and the neighbourhoods, in order to assess the cooling effect of thermal-driven winds and test to what extent the cool air is hampered by the dike. The simulation results would further help to evaluate the ventilation performance of the designed adjustable flood defence structures.

The simulation was done to the three comparative models with only one independent variable, which was the presence of the dike. The model with the original dike represented the current situation that no intervention from the urban climate aspect has been taken. And the model without the dike represented the ideal situation that the dike is completely open for urban ventilation. The last model with part of the dike remained represented the designed structures that are open to some extents, but not completely. The model with part of the dike was a supplemental case to study the relationship between openness and ventilation efficiency.

The first step to start the ENVI-met simulation was defining a working space on the computer. Secondly, the sub-program called SPACES was used to build the digital models as the input for the simulation. The digital model includes buildings, vegetation, soil cover and other environmental conditions that matter to the microclimate process. After the model has been built, using ConfigWizard to define the simulation context, including the timespan, the original weather condition, the location, the orientation, and etc was the last step before running the simulation. Eventually, when everything was prepared, it was time to run the ENVI-met simulation. Three versions of simulation space are there for choosing: (1) 100*100*40, (2) 180*180*35 and (3) 250*250*30. In order to make a successful simulation, it is important to ensure that the simulation space is bigger than the model area. If the model size is similar to the simulation space, results will be invalid on the edge, therefore it is better to choose a big simulation space. However, to run a simulation in the bigger version of space is correspondingly taking more time.

The outcomes of the simulation were a big bunch of data, including air temperature, wind speed and direction, vector speed, air pressure, surface

Figure 4.1.1
The simulation area

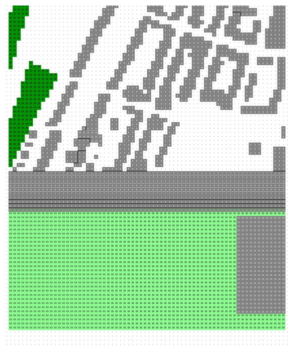


Figure 4.1.2
2D view of the model with the dike

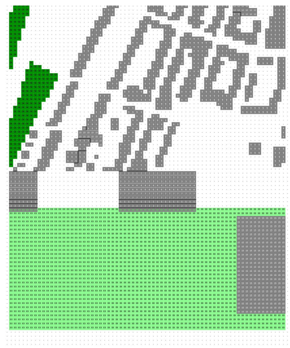


Figure 4.1.3
2D view of the model with partly the dike

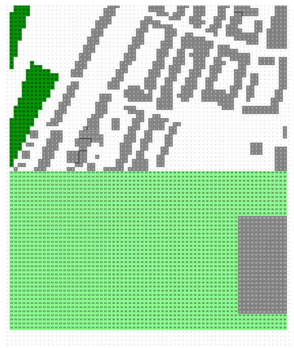


Figure 4.1.4
2D view of the model without the dike

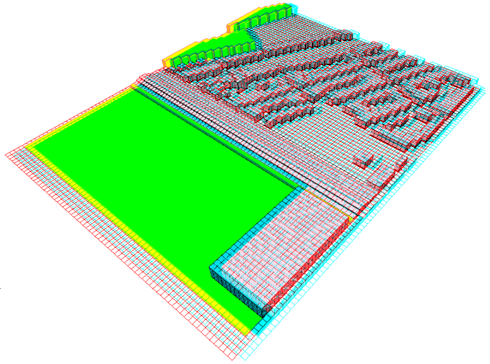


Figure 4.1.5
3D view of the model with the dike

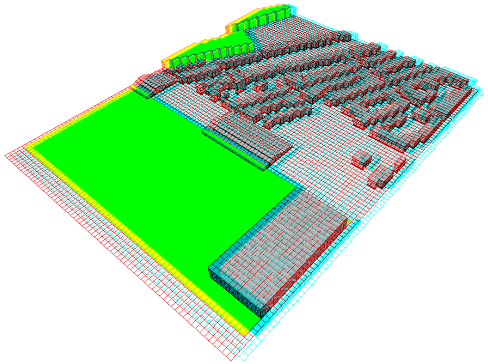


Figure 4.1.6
3D view of the model with partly the dike

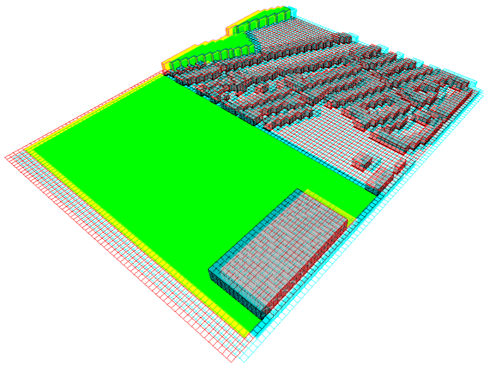


Figure 4.1.7
3D view of the model without the dike

temperature, Tmrt, PMV, and etc. In the end, LEONARDO 2014 was used to visualize these data ("Learning & Support - ENVI-met", 2020).

Modelling

Previous research indicates that the cooling distance of a green area ranges from 200m to 400m nearby (Yu & Hien, 2006). Therefore, my modelling area was decided to be around 400m on the south-north direction from the existing dike towards the neighbourhoods, and approximate 300m on the east-west direction, which is the floodplain excluding the current shipyard.

It should be mentioned that the unit in the model is the grid, instead of metre or other physical lengths. The size of one grid or the so-called grid resolution in SPACES can be chosen from 0.5m to 10m. In order to fit the model into the ENVI-met version of 100*100*40 grids, and considering the size of the street canyon and the dike, the resolution of x-grid and y-grid were decided to be 5m. The size of the model input was therefore 70 grids*90 grids*30 grids, which represents the model area of 450m*350m. For the z-grid, the height of the modelling space has to be at least four times of the tallest object in the model in order to acquire valid simulation outcomes. The tallest building in the model area is a community church called Laankerk (also called Hersteld Hervormde), which is approximately 15m tall. Thus the resolution of z-grid was decided to be 2m. So that the total height of the modelling space was 60m, which is exactly four times of the tallest building. In the end, in order to make a valid simulation, at least one grid, which is 5m in this case, should be left empty.

Figure 4.1.8 The Laankerk ("Geschiedenis – Laankerk.nl", 2017)

4.1.2 Simulation setting

As elaborated in the method, the sub-program called ConfigWizard was used to define the simulation setting including the date, the time span, the initial air temperature, the wind direction & speed and location. The warmest day (26th July) in 2018 appeared in the longest heatwave in decades. So the 26th July was chosen to be the date for the simulation, because, both the cooling demand and the thermal-driven wind on that day were theoretically the strongest in the year.

The floodplain and the neighbourhoods experience the process from receiving solar radiation once the sun rises to losing heat until the dawn, which is a cyclical day. A cyclical day was considered to be the shortest time span that can successfully simulate this microclimate process. For that reason, 24 hours from 6 am 26th to 6 am 27th was loaded in the simulation. For the initial air temperature at 6am, I used the recorded data from the weather station in Rotterdam city, which was 20 °C.

The cool breeze occurs significantly during a calm summer night which refers to the night without regional-scale wind above 1.5m/s (Erell, Dennis., Williamson & Pearlmutter, 2011). In order to create a simulation context that the cool breeze can be identified as clear as possible, the lowest setting of wind speed(0.1m/s) was chosen.

Date: 26th July 2018 (The warmest day in 2018)
Timespan: 24 hours, from 6:00 26th July to 6:00 27th July 2018
Initial air temperature at 6:00 26th: 20 °C
Wind direction: 230 South-west
Wind speed: 0.1m/s
Locations: Rotterdam

From	up to and including	Duration in days	Number of tropical days	Highest temperature ° C	Date of highest temperature
08 Aug 1911	Aug 14, 1911	7	5	33.0	Aug 10, 1911
May 21, 1922	May 25, 1922	5	3	32.8	May 24, 1922
05 Jul 1923	Jul 14, 1923	10	5	33.1	11 Jul 1923
20 Jun 1941	26 Jun 1941	7	3	32.0	23 Jun 1941
06 Jul 1941	13 Jul 1941	8	6	32.2	12 Jul 1941
Aug 14, 1947	Aug 21, 1947	8	3	32.2	Aug. 16, 1947
Jul 26, 1948	30 Jul 1948	5	4	31.3	28 Jul 1948
29 Jul 1975	Aug 15, 1975	18	6	32.9	Aug 8, 1975
23 Jun 1976	09 Jul 1976	17	10	34.9	03 Jul 1976
29 Jul 1982	04 Aug 1982	7	4	31.9	02 Aug 1982
04 Jul 1983	12 Jul 1983	9	3	33.0	11 Jul 1983
26 Jul 1990	04 Aug 1990	10	3	35.3	04 Aug 1990
Jul 19, 1994	31 Jul 1994	13	5	34.1	Jul 24, 1994
29 Jul 1995	03 Aug 1995	6	3	32.3	31 Jul 1995
05 Aug 1997	13 Aug 1997	9	5	32.1	13 Aug 1997
28 Jul 1999	04 Aug 1999	8	3	31.4	01 Aug 1999
Aug 22, 2001	Aug 26, 2001	5	3	31.1	25 Aug 2001
31 Jul 2003	Aug 13, 2003	14	7	35.0	07 Aug 2003
02 Aug 2004	Aug 11, 2004	10	3	32.5	09 Aug 2004
18 Jun 2005	24 Jun 2005	7	3	32.8	20 Jun 2005
30 Jun 2006	06 Jul 2006	7	3	32.0	04 Jul 2006
15 Jul 2006	30 Jul 2006	16	8	35.7	19 Jul 2006
21 Jul 2013	27 Jul 2013	7	3	32.6	Jul 22, 2013
30 Jun 2015	05 Jul 2015	6	3	33.1	01 Jul 2015
Jul 15, 2018	27 Jul 2018	13	4	35.7	Jul 26, 2018
29 Jul 2018	07 Aug 2018	10	4	33.9	07 Aug 2018
Jul 22, 2019	27 Jul 2019	6	4	37.5	25 Jul 2019
Aug 23, 2019	28 Aug 2019	6	3	32.8	27 Aug 2019
Total of 28 heat waves					

Figure 4.1.9 The heatwave records from 1911 to 2019 ("KNMI - Hittegolven", 2020)

4.1.3 Result

In this section, I give an overview of the modelling results. The table of crucial data is shown below, including the legend, the temperature difference between the floodplain and the neighbourhoods in the three models at each picked time point.

The purpose here was to compare the air temperature and the airflow patterns between three models throughout 24 hours. To do that, the simulated data of 13 points in time were visualized: (1) 6:00 26th, (2) 8:00 26th, (3) 10:00 26th, (4) 12:00 26th, (5) 14:00 26th, (6) 16:00 26th, (7) 18:00 26th, (8) 20:00 26th, (9) 22th 26th, (10) 24:00 (midnight) 26th, (11) 2:00 27th, (12) 4:00 27th, and (13) 5:00 27th. These results were taken for every two hours, except for the last group that is from 4 am to 5 am on the 27th of July. The complete simulated results can be found in Appendix 1.

Time	Initial temperature (℃)	Interval (℃)	Class	Height temperature taken (m)	Temperatre contrast (Dike)(℃)	Temperatre contrast (Partly dike)(℃)	Temperatre contrast (No dike)(℃)
8:00 26th July	25	0.25	10	1.8	1.46	1.55	1.58
10:00 26th July	28	0.25	10	1.8	1.28	1.34	1.78
12:00 26th July	30	0.25	10	1.8	2	1.51	1.92
14:00 26th July	32.5	0.25	10	1.8	2.33	1.74	1.7
16:00 26th July	32.5	0.25	10	1.8	2.04	1.84	1.75
18:00 26th July	31.5	0.25	10	1.8	1.16	1.09	1.75
20:00 26th July	29	0.25	10	1.8	-1.06	-0.96	-1.21
22:00 26th July	27	0.25	10	1.8	-1.72	-1.64	-1.85
24:00 26th July	25	0.25	10	1.8	-2.68	-2.42	-2.56
2:00 27th July	23	0.3	10	1.8	-3.25	-3.45	-3.16
4:00 27th July	21	0.35	10	1.8	-4.07	-3.92	-3.84
5:00 27th July	20.5	0.35	10	1.8	-4.44	-4.33	-4.24

Figure 4.1.10 Overview of the simulation results: the temperature range, the temperature contrast between floodplain & neighbourhood, and the legend at each picked time

8:00 26th July 2018

Since the simulation has only started for two hours, the difference in air temperature between the neighbourhoods and the floodplain in the three models are barely visible. The temperature patterns are almost the same, and no thermal-driven air movement or hampering effect can be seen at this moment.

10:00 26th July 2018

Two hours later, when the sun goes higher, the air temperature rises on both sides of the dike. The temperature differences between the floodplain and the neighbourhoods are still below 2°C (1.28°C, 1.34°C, 1.78°C). However, the temperature difference in the model without the dike is bigger than the others. Another unexpected finding is that the air temperature on the floodplain is always higher than the neighbourhoods since the simulation starts. I believe that is caused by the shading of houses in the neighbourhoods.

12:00 26th July 2018

The air temperature on the floodplain is still approximately 1.7°C higher than the neighbourhoods at 12 o'clock. Moreover, in the model with the dike, the coolest area in the neighbourhoods is a bit bigger than the model with part of the dike and without the dike, which indicates that the dike is already interfering the air exchange.

14:00 to 16:00 26th July 2018

In the two hours from 14:00 to 16:00, the highest temperature of the day appears. According to the temperature disparity, the cool breeze from the floodplain towards the neighbourhoods is not happening yet, at least not as expected. However, the temperature difference between the floodplain and the neighbourhoods in the model without the dike becomes the smallest, while it was the biggest in the morning.

18:00 to 20:00 26th July 2018

Even though the sunset would happen at 21:41, which is almost two hours after this point in time, the area doesn’t receive the solar radiation as much as before in the period from 18:00 to 20:00. The two groups of simulated results (Figure 4.1.14, Figure 4.1.15, Figure 4.1.16, Figure 4.1.17, Figure 4.1.18 and Figure 4.1.19) indicate a consequence of that, which is the reversing of temperature distributing. The air temperature on the floodplain drops faster than the neighbourhoods due to its openness and green cover.

22:00 26th July 2018

After the sunset, the air temperature difference becomes more extreme, because of the absence of shortwave radiation. As indicated in Figure 4.1.22, the relatively warm area in the model without the dike is smaller than the model with part of the dike (Figure 4.1.21) and the model with the original dike (Figure 4.1.20). Specifically, in the model without the dike, the two blocks near the dike are in the zone where the air temperature is 0.5°C lower than the same zone in the model of the current situation. Moreover, in the model without the dike, even the cool area on the floodplain is bigger than the model with the dike.

On the floodplain, the heat emits to the air without obstacles. Conversely in the neighbourhoods, the longwave radiation is trapped in the street canyons, which makes the UHI effect stronger after sunset, and the cool breeze more demanded in the evening and during the night. Later in the night, the hampering effect caused by the dike would be more significant.

Midnight

As indicated in Figure 4.1.23, Figure 4.1.24 and Figure 4.1.25, the air temperature difference between the neighbourhoods and the floodplain continues getting bigger in both the three models. At the same time, the relatively cooler area in the model without and with part of the dike is becoming bigger than the other, which implies the hampering effect is happening to the cool air exchange more significantly.

2:00 27th July 2018

The temperature patterns in the three models remain stable after the midnight, but the temperature difference continues getting bigger and reaches almost 4°C around 2 am.

4:00 to 5:00 27th July 2018

The temperature difference between the two topographies reaches its peak (around 4.5°C) before the dawn. In the Figure 4.1.26, Figure 4.1.27 and Figure 4.1.28, the patterns are clearly showing that the cool area expands into the neighbourhoods in the model without a dike and with part of a dike, which means the bigger cooling range. It is believed that is caused by more efficient ventilation. On the other hand, in the model with the original dike, the warm zone reaches the inner bottom of the dike, and the neighbourhoods receive no cooling effect from the land outside the dike.

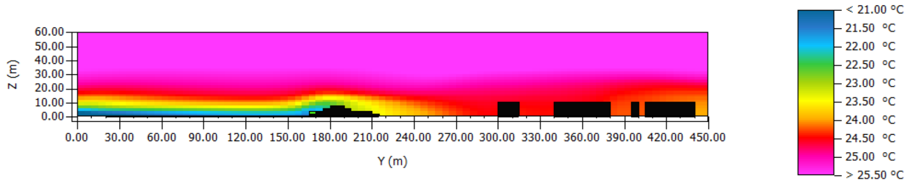


Figure 4.1.11 Temperature profile in ℃ in the model with the dike at 4:00, 27th, 2018

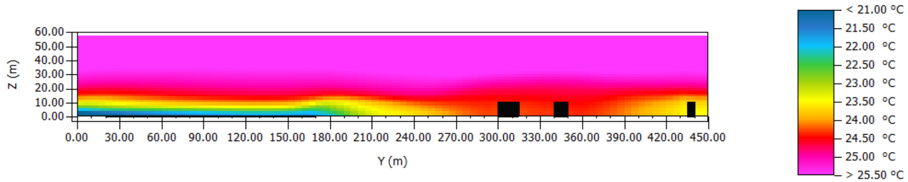


Figure 4.1.12 Temperature profile in ℃ in the model with part of the dike at 4:00, 27th, 2018

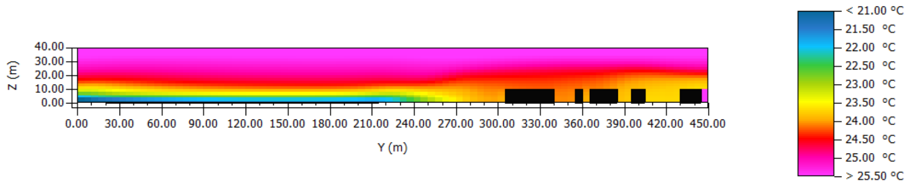


Figure 4.1.13 Temperature profile in ℃ in the model without the dike at 4:00, 27th, 2018

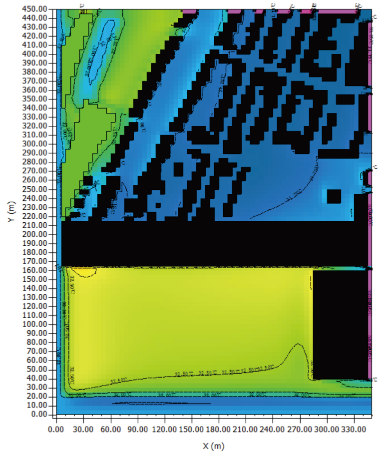


Figure 4.1.14
Temperature pattern in ℃ in the model with dike at 18:00, 26th, 2018

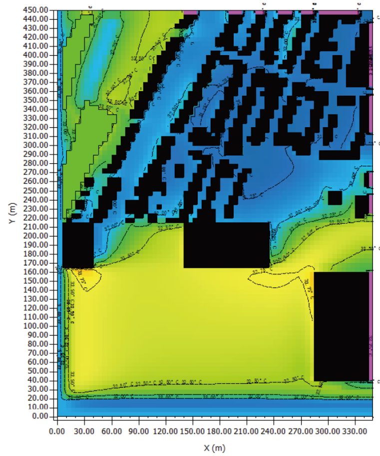


Figure 4.1.15
Temperature pattern in ℃ in the model with partly dike at 1.8m, at 18:00, 26th, 2018

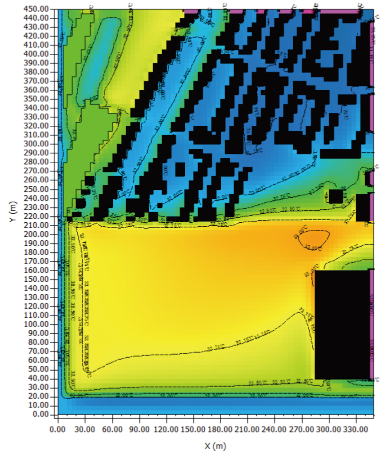
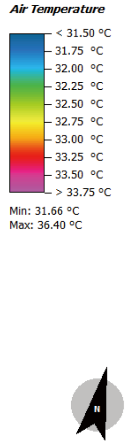


Figure 4.1.16
Temperature pattern in ℃ in the model without dike at 1.8m, at 18:00, 26th, 2018



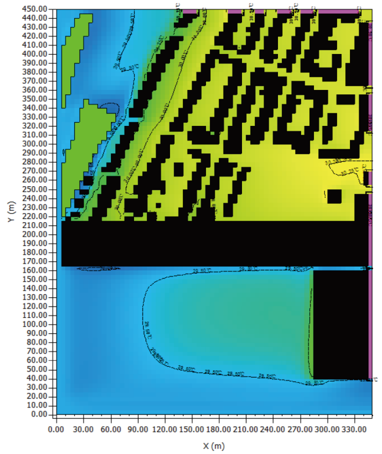


Figure 4.1.17
Temperature pattern in ℃ in the model with dike at 20:00, 26th, 2018

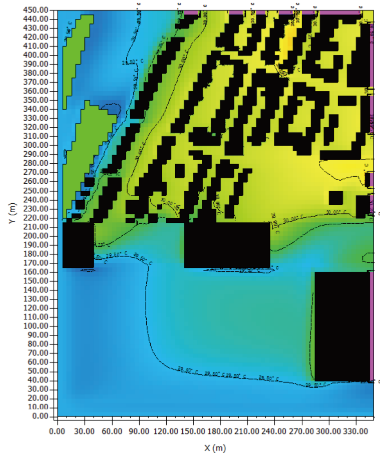


Figure 4.1.18
Temperature pattern in ℃ in the model with partly dike at 1.8m, at 20:00, 26th, 2018

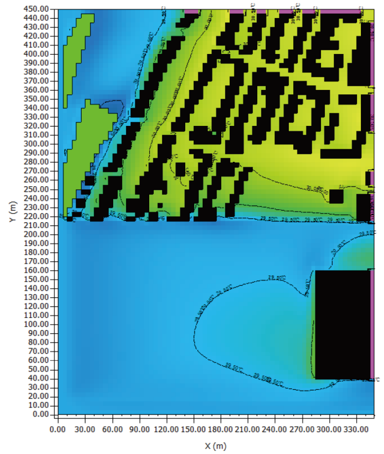
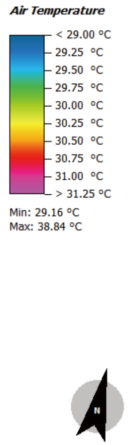


Figure 4.1.19
Temperature pattern in ℃ in the model without dike at 1.8m, at 20:00, 26th, 2018



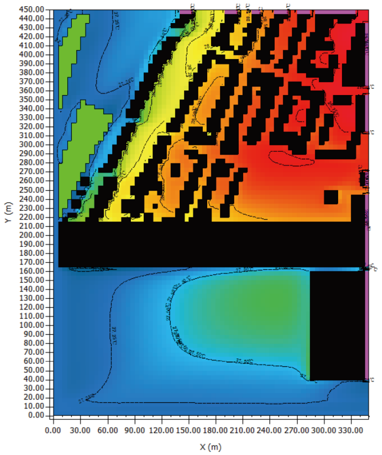


Figure 4.1.20
Temperature pattern in ℃ in the model with dike at 22:00, 26th, 2018

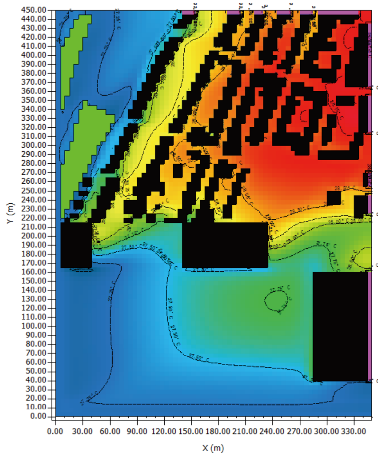


Figure 4.1.21
Temperature pattern in ℃ in the model with partly dike at 1.8m, at 22:00, 26th, 2018

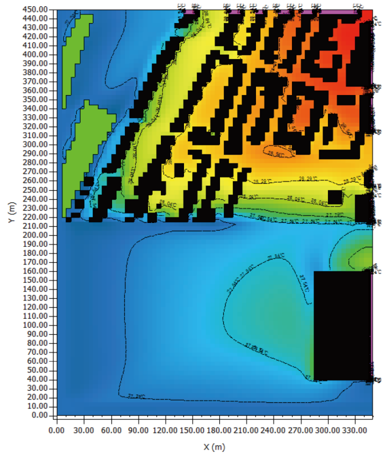
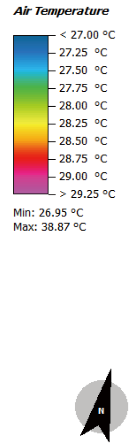


Figure 4.1.22
Temperature pattern in ℃ in the model without dike at 1.8m, at 22:00, 26th, 2018



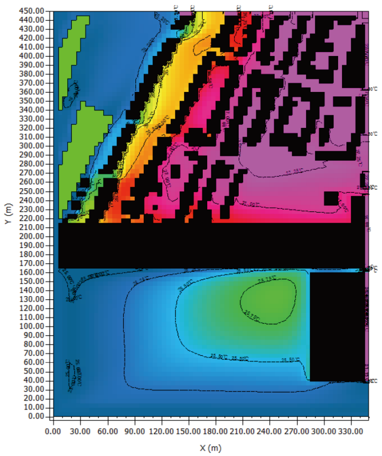


Figure 4.1.23
Temperature pattern in ℃ in the model with dike at the midnight, 27th, 2018

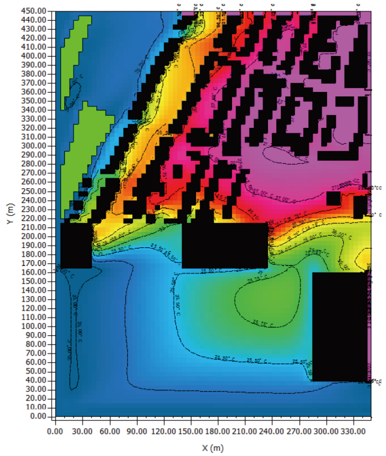


Figure 4.1.24
Temperature pattern in ℃ in the model with partly dike at 1.8m, the midnight, 27th, 2018

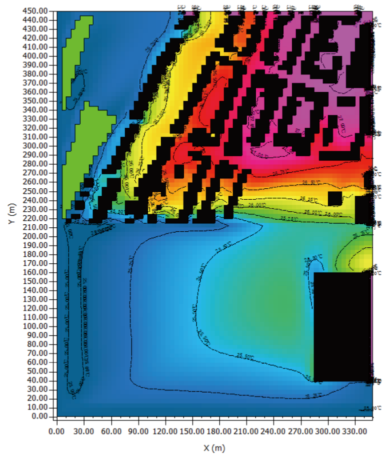
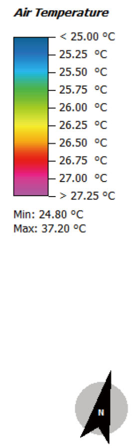


Figure 4.1.25
Temperature pattern in ℃ in the model without dike at 1.8m, the midnight, 27th, 2018



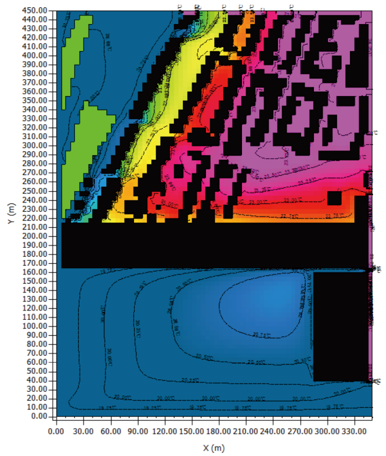


Figure 4.1.26
Temperature pattern in ℃ in the model with dike at 5:00, 27th, 2018

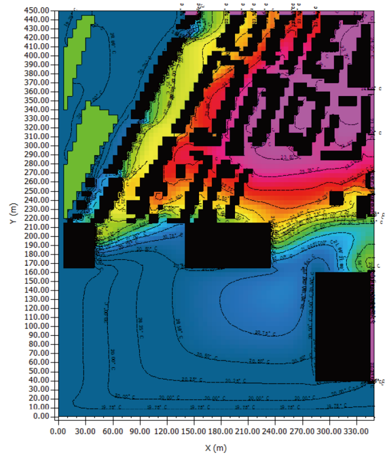


Figure 4.1.27
Temperature pattern in ℃ in the model with partly dike at 1.8m, at 5:00, 27th, 2018

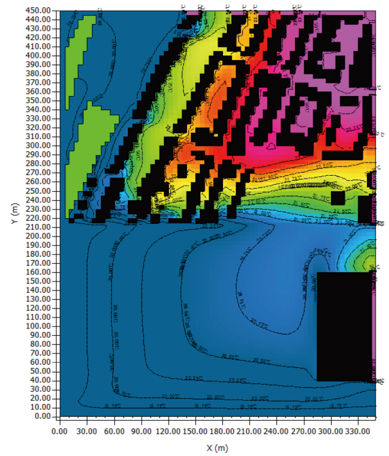
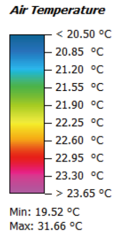


Figure 4.1.28
Temperature pattern in ℃ in the model without dike at 1.8m, at 5:00, 27th, 2018



4.1.4 Summary

Through the microclimate simulation, the SRQ1 has been answered: **To what extent does the dike hamper the cool air exchange?** As these results indicate, the floodplain cools down faster than the neighbourhoods, which leads to a strong temperature difference up to 4.5°C in the night. Due to that temperature difference, the cool breeze is evoked.

Next to that, the comparison between the three models shows the fact that the dike starts to hamper the cool air exchange around 18:00. The model without a dike has the strongest cooling effect and the biggest cooling range, followed by the model with part of a dike remained. And the model with the original dike receives almost no cooling from the floodplain. To be specific, in the model without a dike, the cool breeze can decrease the air temperature on the area of 180m into the neighbourhoods on pedestrian height (1.8m). It is worth to mention the effect was measured in the first 24 hours of simulation, and is likely to accumulate. This quantitative study gave an instruction about assessing ventilation efficiency. The more openness in the dike results in more efficient ventilation.

In addition, the outcomes of the simulation are consistent with the prediction in previous research that the cool breeze or the so-called intra-urban thermal breeze (IUTB) appears only at night, not during the daytime (Erell, Dennis., Williamson & Pearlmutter, 2011).

4.2 Concept designs for 'synergistic dike'

First of all, the new flood defence structures need to be able to open for cool air exchange and close for flood protection. In this phase, the design was meant to be on the concept level. Unlimited and unrestricted solutions were welcomed in order to collect as many ideas as possible. Eventually, the eight concept flood defence models were proposed:

The inflatable dike partition
The rotatable dike partition
The windows in the dike
The modular & moveable floodwall
The 'drawbridge' dike partition
The rotatable portadam
The sliding floodgate
The gabion dike

Secondly, their performance regarding the efficiency of cool air exchange was assessed, which later determined the selection for the further development. According to the conclusion from those ENVI-met simulation, the structures that provide more openness achieve better ventilation, therefore, the openness level of the concept models was the selection criteria. In order to compare their openness, a group of diagrams showing the projection of the each concept model in the ventilation direction were made. Based on those, the selection was made in the end of this Design Loop.

Besides ventilation efficiency, other aspects were also taken into consideration during the production of the eight concept models, including their applicability, operational convenience, maintenance issues and costs.

4.2.1 Inflatable dike partition

The rubber barrier technic is well-developed, and has been applied worldwide to serve different purposes. It is a hollow rubber bladder that can be inflated and deflated for multiple times (Zhang, Tam, & Zheng, 2002). In order to make the flood defence structure adjustable, I use it to replace the original dike. On average, inflation is required once a year to prevent flood. In the Netherlands, the rubber partition technic has been applied at IJssel delta near Ramspol, which has protected Overijssel against the water from the Ketelmeer for years. There are three options for the medium to fill in the rubber bladder: (1) air, (2) water and (3) a mixture of water and air. The water-medium rubber structures are used more often when it relates to flood. The water filling in is normally from the river or a reservoir nearby for water storage, and gets pumped through underground pipes into the rubber bladder (Zhang, Tam, & Zheng, 2002).

The time for rubber membrane to fully operate depends on its protection height, mostly within an hour. The inflation process requires no manual operation but a flood forecast. In addition, hydronic engineers have mentioned the below structure of a rubber partition is inexpensive to install and maintain ("Flood protection by an inflatable rubber dam: Balgstuw Ramspol", 2020). Most of the year, the rubber bladder is flat and can be hidden on the ground when flood defence is not needed. Therefore, this structure is considered very useful to make an opening in the dike, which is completely open in the ventilation direction.

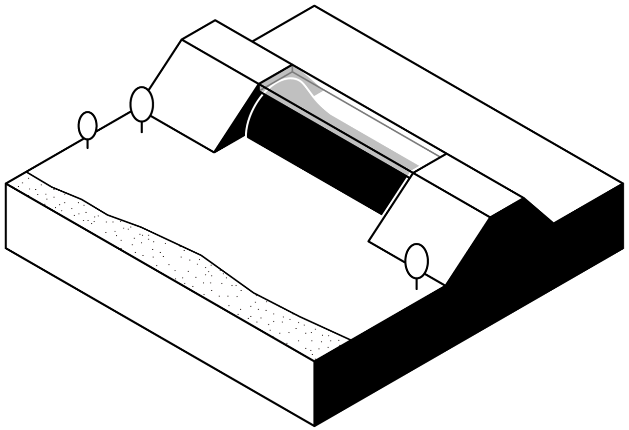


Figure 4.2.1 The Inflatable dike partition

Figure 4.2.2
The projection of inflatable dike partition in the ventilation direction

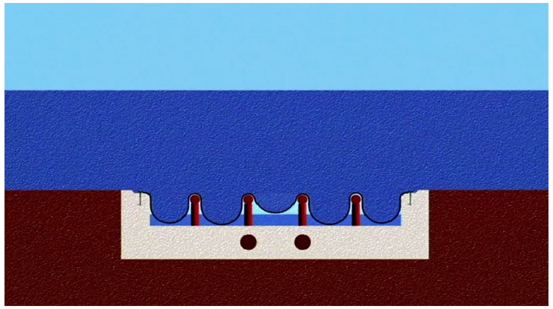


Figure 4.2.3
The operational process of Ramspol Inflatable Dam when deflated ("Flood protection by an inflatable rubber dam: Balgstuw Ramspol", 2020)

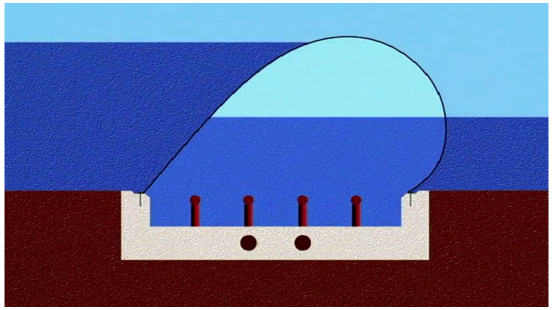


Figure 4.2.4
The operational process of Ramspol Inflatable Dam when inflated ("Flood protection by an inflatable rubber dam: Balgstuw Ramspol", 2020)

Figure 4.2.5
The rubber dam of the Tempe Town Lake in Tempe, Arizona ("File:Tempe Town Lake - West Dams - 2009-09-04.JPG - Wikimedia Commons", 2009)

4.2.2 Rotatable dike partition

The idea of this rotatable dike partition was from window shutters. The shutter is a window frame with a group of rotatable blinds for controlling the amount of solar radiation entering the room, in order to provide shading or privacy. If the airflow and water are imagined as sunlight, the 'shutter' structure is useful to achieve the operation of open-close. The gap in the dike can be closed by rotating those 'blinds' to a certain angle, which formulates a water-retaining element. The height of water-retaining element is adjustable by activating the certain amount of 'blinds'. Additionally, by designing the size and the vertical layout properly of those rotating elements, the structure can be used for other purposes, such as an auditorium or benches.

The thickness of those water-retaining elements cast shadows on the projection when they rotate to the horizontal position for ventilation. The cool air can only penetrate through the gaps between those water-retaining elements. The 'blinds' might have an impact on ventilation performance, especially those on the lower level. Since that, the rotatable dike partition is considered to be partly open on the ventilation direction.

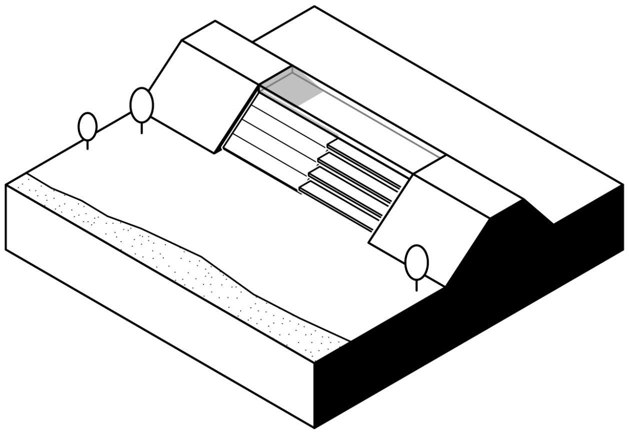


Figure 4.2.6 The rotatable dike partition

Figure 4.2.7
The projection of rotatable dike partition in the ventilation direction

Figure 4.2.8 The window shutter

4.2.3 Windows in the dike

The window in the dike is basically a tunnel cross the dike on the ground level. Since the cool air always remains on the ground level, they can penetrate the dike via these 'windows'. Meanwhile, pedestrians and cyclists can also use the tunnel to cross the dike, which saves the trouble of crossing the traffic on the dike crest.

The small breaches in the dike are often for other purposes, mainly traffic. According to examples, the so-called 'coupure' in the dike is usually 6m wide which is the width of a double-lane road. A group of strips made of wood or metal are often used to close the 'coupure'.

In the new design, in order to close the ventilation window efficiently, the width of them should not be more than the average size of a 'coupure' (5m to 6m). Regarding the scale of dike rings and floodplains, windows are rather tiny, therefore their cooling effect is limited. For that reason, windows in the dike are considered to be partly open.

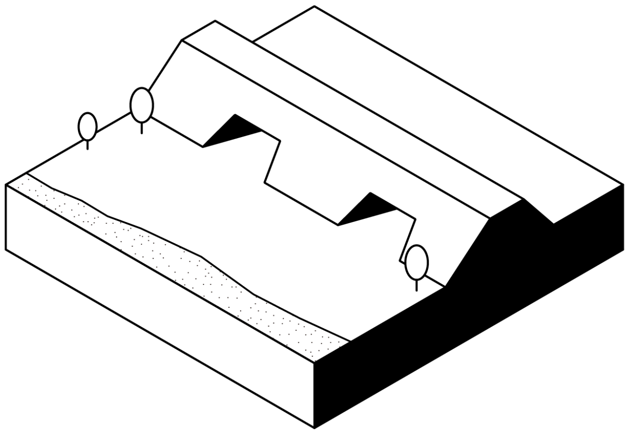


Figure 4.2.10 The windows in the dike

Figure 4.2.11
The projection of windows in the dike in the ventilation direction

Figure 4.2.12
The pedestrian tunnel in the dike near the Westpark, Amsterdam

Figure 4.2.13
The bulkheads close the coupure on the Boterdijk (Hendriks, 2019)

4.2.4 Modular & moveable floodwall

In the Netherlands, a small 'coupure' in the dike for different purposes can be found frequently. Averagely the opening is limited to the width of a double-lane road (5m to 6m). In most of cases, the moveable flood defence elements made of either wood, cement or metal have been used to close a 'coupure' temporarily. Temporary flood defence elements are stored closeby because a quick reaction is important.

For the ventilation purpose, a wider opening in the dike is expected. Correspondingly, more materials are needed to close the enlarged ventilation 'coupure', which leads to the storage problem of a big amount of defence elements. From the viewpoint of storage, placing the temporary defence element on the ground was proposed as the solution. When the land is not threatened by flood, all of the modular and moveable defence elements stay on the ground, so that the cool air can exchange with the warm just above them. In the wet season, those modular defence elements are pulled up and formed into a temporary floodwall. In the dry season, the structure can be invisible and completely open for ventilation.

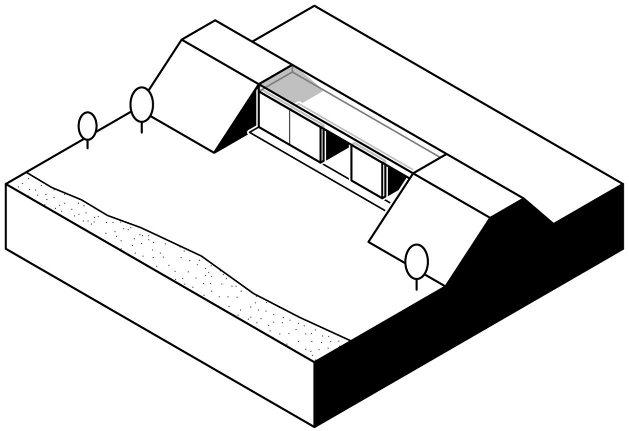


Figure 4.2.14 The moveable flood-wall

Figure 4.2.15
The projection of moveable floodwall in the ventilation direction

Figure 4.2.16
The coupure van Baarlo

Figure 4.2.17
The bulkheads storage (Henkv, 2014)

Figure 4.2.18
The gate in flood defence wall near to West Bay, Dorset, Great Britain (Mykura, 2014)

Figure 4.2.19
The floodwall at Zruč nad Sázavou, Czech Republic ("File:Zruč nad Sázavou, Ostrovský potok, u Vlašimské ulice.jpg - Wikimedia Commons", 2013)

4.2.5 'Drawbridge' dike partition

The 'drawbridge' dike partition is a variant hybrid of the window in the dike and the moveable floodwall. Unlike the dike window, which is closed with a group of 'stop-log' flood defence elements in the middle, I got inspiration from the drawbridge. Rotatable plates are used to close the hollowing part in the dike from outside. The rotatable water-retaining element is made of steel, and connected to a rotating device on the ground level. During the dry season, the steel plates lie on the ground to let the cool breeze penetrate the dike. Before flood coming, those steel plates get pulled up by the chain and attach to the upper part of the dike. The hollowing part in the dike can be enlarged by placing the 'drawbridge' next to each other.

This structure is almost completely open in the ventilation direction, but steel plates of certain thickness and rotating devices are obstacles on the ground where high-density cool air is supposed to exchange. For that reason, the 'drawbridge' dike partition is considered to be better than 'partly open' but not completely open.

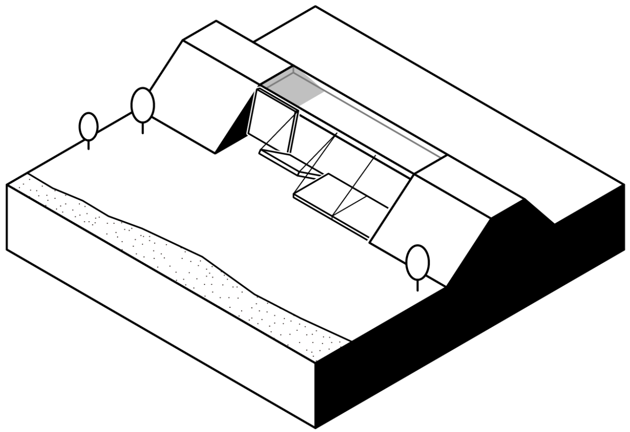


Figure 4.2.20 The 'drawbridge' dike partition

Figure 4.2.21
The projection of 'drawbridge' dike partition in the ventilation direction

Figure 4.2.22
The drawbridge at Threave Castle ("Attacking and defending castles", 2020)

4.2.6 Rotatable portadam

The portadam is a lightweight triangular frame, covering with plastic sheets. The structure is mostly used to provide temporary water protection for individual industrial objects, such as bridge piers during constructions.

The new flood defence model was made based on the portadam structure and the reference flood defence element (Figure 4.2.25). This reference flood defence element was used to allow changes of the spatial plan over time in the coastal planning project of Bolivar Peninsula (Bedient, et al., 2015). However, detail information about this rotatable triangular structure was not found.

Herein, the dike was replaced by the rotatable portadam for the purpose of urban ventilation. During most of the year, the structures stand as a group of shading pavilions which allow the the cool air to flow underneath them. The pillars, which are also the rotation axis of the water-retaining elements, are installed on the ground. The pillars will not be obstacles to the cool breeze due to their limited volumes in the ventilation direction.

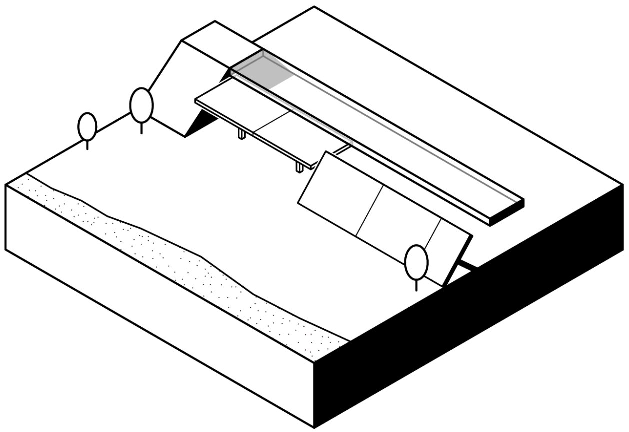


Figure 4.2.23 The rotatable portadam (Based on Van den Ende, 2015)

Figure 4.2.24
The projection of rotatable portadam in the ventilation direction

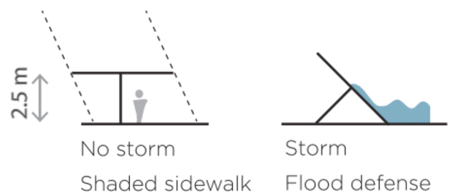


Figure 4.2.25
The temporary flood defence element in the project of Bolivar Peninsula (Bedient, et al., 2015)

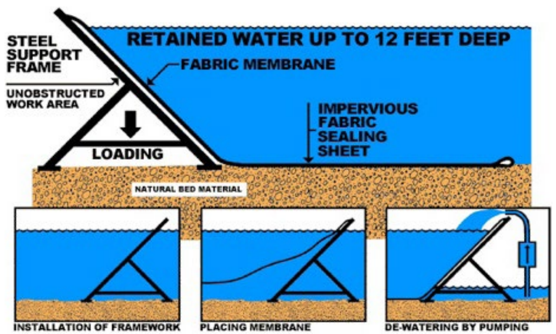


Figure 4.2.26
The working procedure of Portadam ("Portadam", n.d.)

4.2.7 Sliding floodgate

The design of this concept model was inspired by the toy called ‘Jenga’. Players take turns to remove a woodblock at one time from the tower and place the block on the top of the tower, trying to keep the structure from collapse. The horizontal movement of woodblocks creates cavities on the tower. From there, the sliding flood defence model was formed. A defence element that can move forward and backward to open and close the cavity in the dike was the primary idea of the sliding floodgate.

The sliding floodgate consists of a pair of matched water-retaining elements. Wheels and rails are installed under the sliding elements. In dry season, the pair of ‘gates’ are slid towards the opposite directions, which leaves a cavity where the cool air can flow across the dike. By reuniting the two sliding elements, the floodgate is closed. The sliding floodgate can be placed next to each other, in order to have more ventilation channels. However, when the sliding floodgate is open, the ventilation channel is not straight. According to the current ENVI-met simulation, it was unable to evaluate if the corner in the ventilation direction have a negative impact on ventilation efficiency.

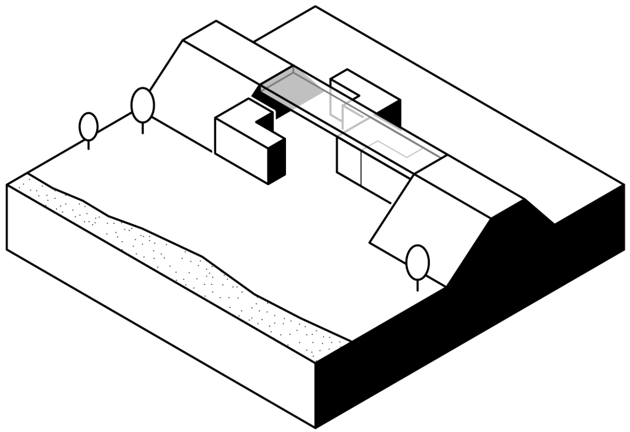


Figure 4.2.27 The sliding flood-gate

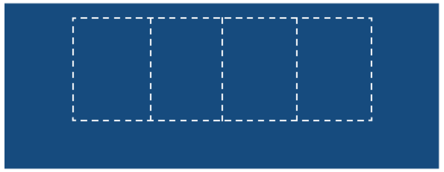


Figure 4.2.28
The projection of sliding floodgate in the ventilation direction

4.2.8 Gabion dike

The term 'gabion wall' is describing a metal grid filled with cracked rocks or cobstones on site. This design enlarged the gabion structure to the height of a dike. And sandbags are filled into the gabion when flood comes. During dry seasons, the cool breeze can penetrate the gabion grid when sandbags are absent.

Amongst all kinds of temporary flood protection, the sandbag wall is used very often as an emergency measure to build the defence line, even though their stability and strength are almost unpredictable. However, in the gabion dike model, the sandbag wall will be more organized and robust with the support from the gabion grid. In addition, the height of the sandbag wall is adjustable according to the yearly predicted flood amount. Comparing to the other alternatives, closing the defence line by filling in sandbags requires more time, which means a more advanced flood forecast is required.

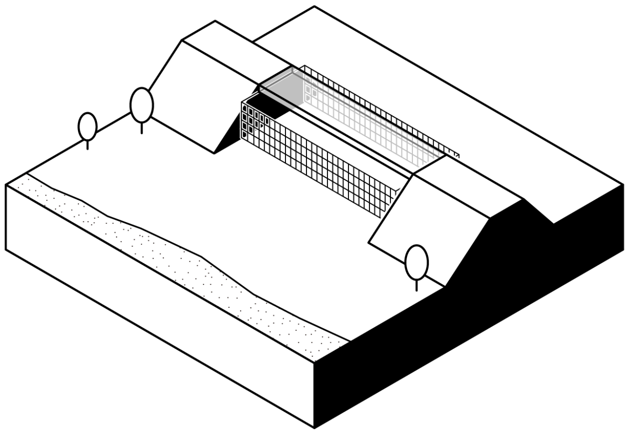


Figure 4.2.29 The gabion dike

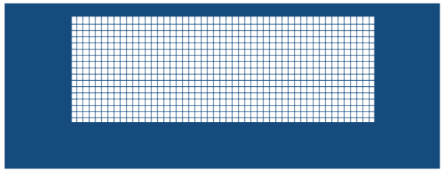


Figure 4.2.30
The projection of gabion dike in the ventilation direction

Figure 4.2.31 The gabion wall

Figure 4.2.32 The grid of a gabion wall

Figure 4.2.33 The sandbag wall in practice

4.2.9 Selection of suitable synergetic dike solutions

In the research through design process, until the selection of concept models that outperform in ventilation efficiency, the design loop about microclimate has been concluded.

According to the conclusion from the ENVI-met simulation, the openness level of the concept models was the selection criteria. The projection of the each concept model in their ventilation direction helped to assess their openness levels, which were described into the three levels: (1) completely open, (2) mostly open and (3) partly open. **The inflatable dike partition, the modular & moveable floodwall, the rotatable portadam** and **the gabion dike** were considered to be on the first level, followed by **The 'drawbridge' dike partition** which is considered mostly open. The others were assessed to be partly open.

At the end of Design Loop 1, only the models that are completely open in the ventilation direction would be selected and further developed in the next design loop. On the other hand, the rest four options remained on the concept design level as a part of the answer to SRQ2.

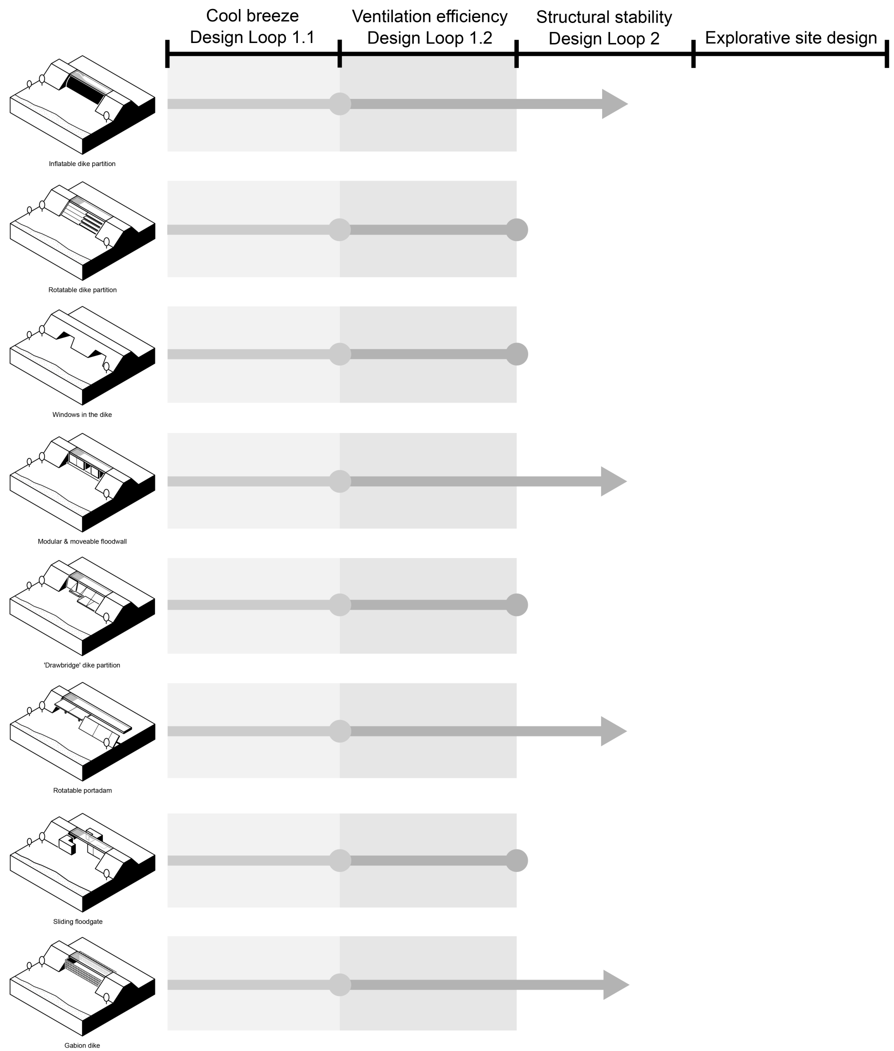


Figure 4.2.34 Overview of selection results until the end of DL1

4.3 Assessing solutions on stability

4.3.1 Introduction

In this chapter, the works of Design Loop 2 are described. I elaborate on how the four selected concept models were further developed and improved from the viewpoint of structural stability. The outcome of Design Loop 2 is the selection of most promising structures that have the most stable flood defence ability, which would eventually answer SRQ2: **How can the adjustable dike structure optimize the flow of a cool breeze?**

In Design Loop 2, I aimed to refine the adjustable dike structure based on the concept models to provide sufficient stability and avoid possible failure mechanisms. Dike failure means water flows across the flood defence, which can happen in four ways: (1) water flows over, (2) under, (3) through and (4) around the structure (Voorendt, 2017). Regarding the fact that civil engineering calculation was unrealistic in this research, the structural stability was assessed according to the criteria, supplied with reference examples study. The criteria was established based on the theoretical framework of multifunctional flood defence. Generally, the design loop of stability was an iterative process, including assessment and adjustment.

The selection criteria has two parts: the crucial elements and the capabilities to avoid possible failure mechanisms. The crucial elements are (1) the water-retaining element, (2) the supporting element and (3) the transition to subsoil (van Veelen, Voorendt, & van der Zwet, 2015). As mentioned in the theoretical framework, the nine potential failure mechanisms of multifunctional flood defence should be avoided, so they were used in the criteria: the capability to avoid (1) erosion between elements and the foundation, (2) leaking in between elements, (3) vibrations from objects that weaken the defence structure, (4) piping, (5) instability of the object, (6) insufficient strength of the object, (7) non-closure of gates, (8) overflow or overtopping of gates and (9) falling objects (Voorendt, 2017). As far as no additional objects except the flood defence element and the bridge were placed in this phase, the failure mechanism 5, 6 and 9 are not a concern, for this reason, they were excluded from the selection criteria.

On top of the structural stability, not only the form and the size of the structure were designed aiming to provide a comfortable use at human scale, but also materials were discussed. For the purpose of presenting the results efficiently, the technical section was decided to be the way to deliberate the technical designs because it doesn't only expose the hidden bearing structures and the crucial connections, but also displays the spatial relationship between users and the structures.

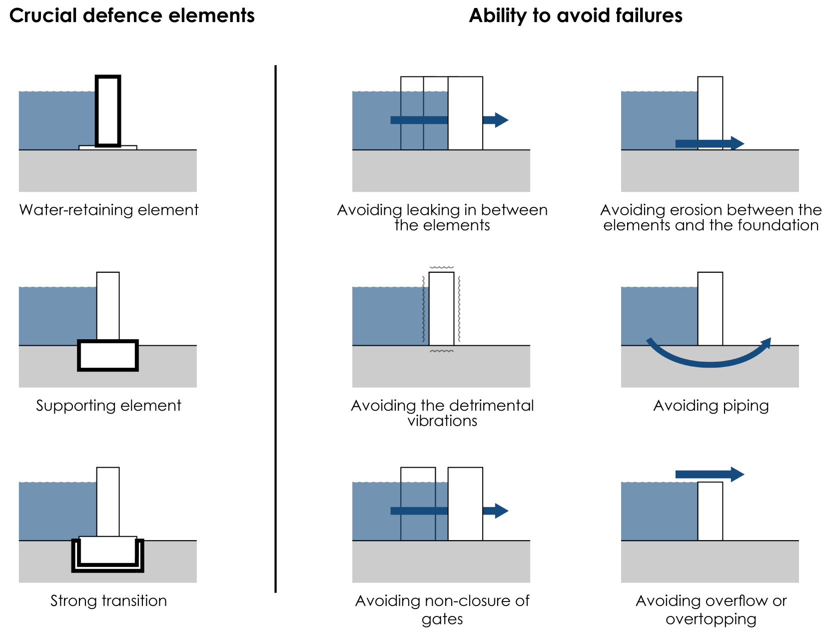


Figure 4.3.1 Selection criterias

4.3.2 Technical design of the inflatable dike partition

The inflatable and deflatable rubber bladder have been applied all over the world to stop water. It is a simple but useful, flexible but robust innovative hydraulic structure. It has been used for multiple purposes, including irrigation, tidal surge barriers, hydraulic power generation, environment control and recreation (Zhang, Tam, & Zheng, 2002), but never for urban climate improving.

A complete inflatable rubber defence structure consists of the four elements: (1) the rubber membrane, (2) the concrete foundation, (3) the control room with water/air pumping devices and (4) the piping system (Zhang, Tam, & Zheng, 2002). There are three options for the medium to fill in the rubber membrane: (1) air, (3) water or (3) a mixture. The air-filled structure requires simpler construction and is easier to operate, but less stable than the water-filled. Conversely, the water-filled and mix-filled structure need a more complex piping system and sometimes a reservoir for water storage to fill in the bladder when the river water is not sufficient (Zhang, Tam, & Zheng, 2002).

The defence height is adjustable by controlling the amount of filling medium. For the water-filled rubber bladder, the circumference of the rubber membrane on the profile should be 4.8 times of the defence height (Zhang, Tam, & Zheng, 2002). This formula helped me to calculate the proper width of the foundation in my technical design.

In former examples, inflatable rubber bladders were mainly used as dams, instead of dikes, because the necessity of adjustable dikes has never been practised. The first rubber dam in history was constructed on the Los Angeles River in 1950 (Figure 4.3.2). And the well-known project in the Netherlands is the Ramspol Inflatable Dam (Figure 4.3.3, Figure 4.3.4). In the case of Ramspol Inflatable Dam, the water filled in the rubber bladder is pumped through the underground pipe system from the river. The rubber membrane is able to reach its full height within an hour ("Flood protection by an inflatable rubber dam: Balgstuw Ramspol", 2020). The difference between a dam and a dike is their relationship with water. The dam touches water on both sides, but not always, conversely the dike only engages with water on one side. The rubber dam receives water pressure from both upstream and downstream, which might help to stabilize it. The rubber dike would only receive pressure from one side, therefore extra supports should be considered.

In my technical design, the bridge provides a frame on both the longitudinal

Figure 4.3.2
The rubber dam on the Los Angeles River (Barden, 2016)

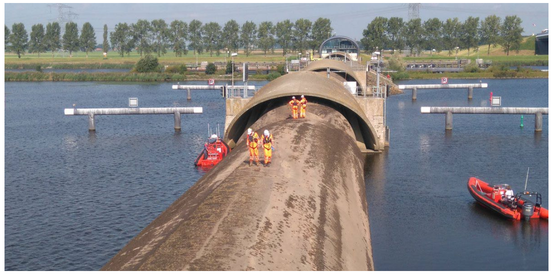
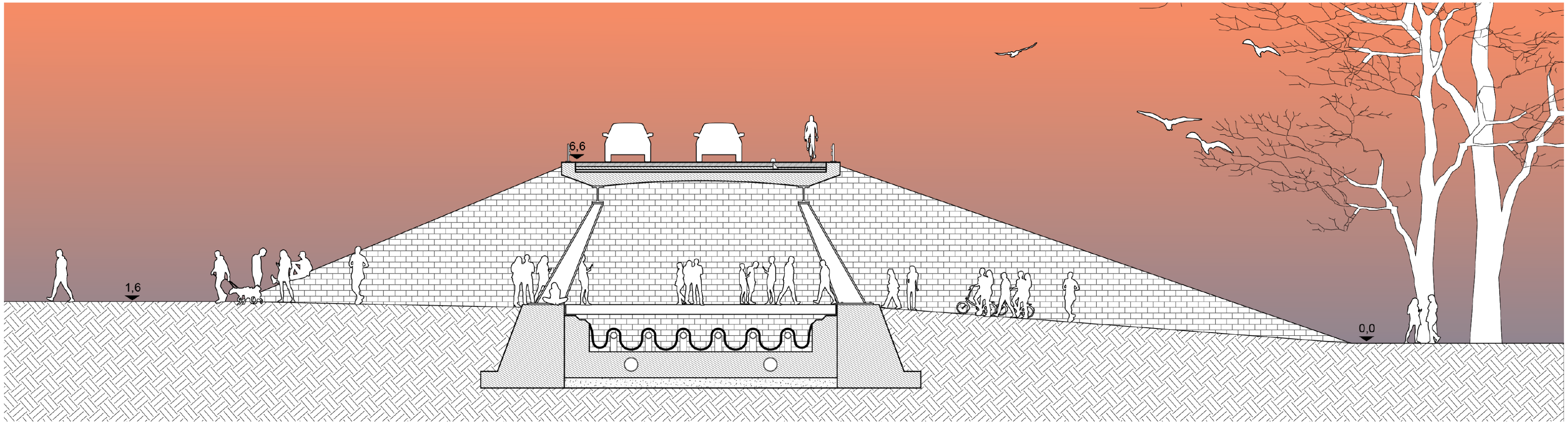


Figure 4.3.3
The Ramspol Inflatable Dam when inflated

Figure 4.3.4
The Ramspol Inflatable Dam when deflated

Figure 4.3.5
Application of metal grid panel as pavement ("Pressed grating - OMAF - Grigliati Pressati", 2018)

Being flat and covered in summer for ventilation



Pumping up in 10 minutes when flood comes

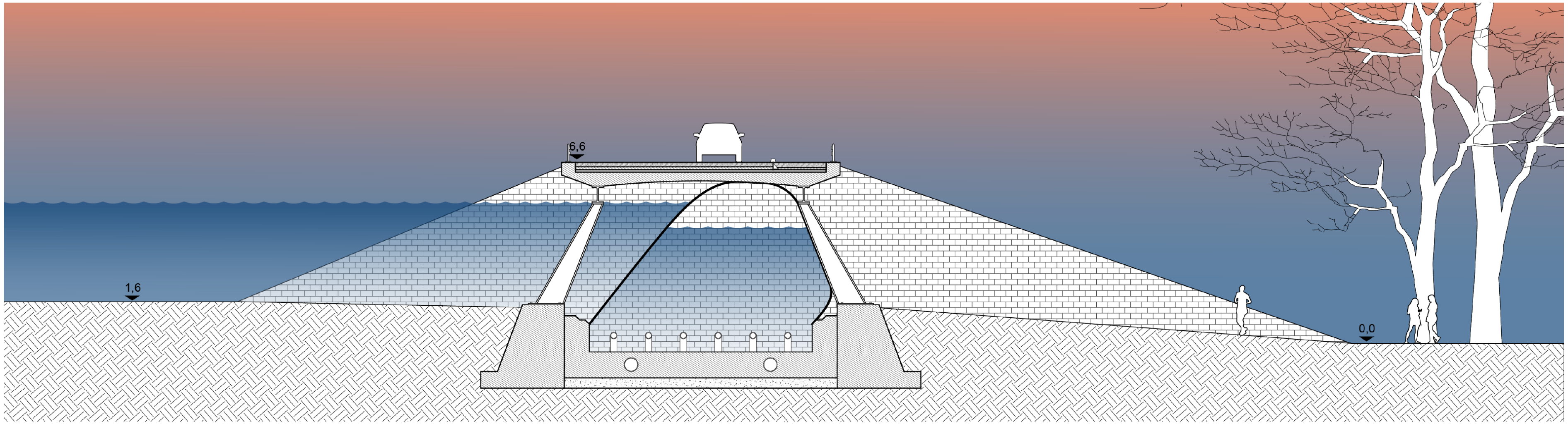


Figure 4.3.6 Technical sections of the inflatable dike partition in the dry season and during a flood event

and lateral directions, which is able to restrict and support the rubber membrane (Jackson III, 1987). According to my calculation, the circumference of rubber membrane on the profile needs to be 24m in order to let the rubber bladder reach the bottom of the bridge (5.5m), so that it closes the cavity under the bridge completely. Correspondingly, the concrete foundation where the bridge pillars stand needs to be 12m wide, which is wider than the double-line road on top. Moreover, if pillars connect to the bridge deck on the edge, the strength of the bridge deck in the middle is weakened (Hambly, 1991). For the reasons above, I integrated a bike path with the double-lane road on the broadened bridge deck. Moreover, the pillars were set into a trapezoidal structure, on one hand, to avoid possible conflict with the rubber bladder, on the other hand, to support the bridge deck from a less edge position, which enhances the bridge stability.

The inflation is required averagely once per year, the rubber bladder reaches the bottom of the bridge, which achieves the defence height of 6.5m that is the original dike height. When flood defence function is not needed, the rubber membrane is deflated and stored in the concrete foundation. Light metal grid panels (Figure 4.3.5) are used to cover the deflated rubber bladder. The metal panels would not touch the rubber membrane but land on the edges of the concrete foundation.

Regarding the selection criteria, the rubber bladder is the water-retaining element, and the concrete foundation and the frame formed by the bridge are the supporting elements. A strong transition to the subsoil has to be achieved by a good quality construction of the foundation. As for the possible failure mechanisms, firstly, erosion between the rubber membrane and the foundation is unlikely to happen, which has been tested by many practice. However, detrimental vibrations are the main cause of abrasion and tear of the rubber body. After that, leaking in between elements and non-closure of gates are not possible as far as the rubber bladder is in one piece. To sum up, the stability of the inflatable dike partition was confirmed.

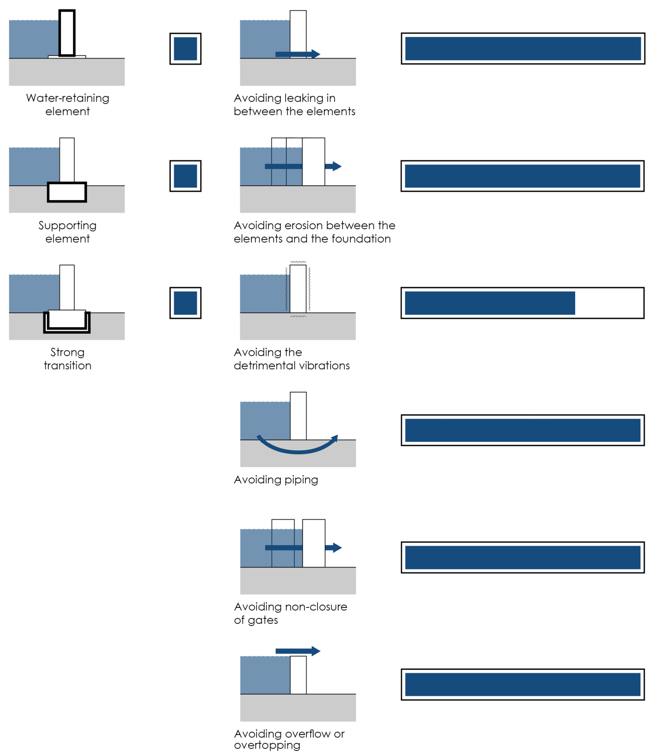


Figure 4.3.7 Assessment of the inflatable dike partition according to the selection criteria

4.3.3 Technical design of the modular & moveable floodwall

Moveable elements for temporary flood defence have a name called ‘stop-log dike’ (Biggar & Masala, 1998). The most common product on the market is a group of hollow metal rectangular units that are placed one above another into a vertical steel frame. This measure has been widely applied in Europe. The stability of them is considered very high as long as the foundation is established properly (Biggar & Masala, 1998). The material of the ‘stop-log dike’ is normally aluminium, which is low-weight but expensive. Since the storage problem is solved by putting defence elements on the ground, which makes no transportation needed, integrated elements and cheaper but heavier materials, such as concrete slabs, become feasible.

In the technical section, the slabs are pre-made reinforced concrete. The design consists of the movable slabs (6m*6m*0.2m) and the concrete foundation that is integrated into the bridge foundation. When the slabs lay down, they fit into the reserved cavities on the foundation. By doing that, the surface of concrete slabs is equal to the adjacent ground. In flood seasons, the slabs are pulled up and placed next to each other to form a 5.5m tall flood defence wall. In order to provide sufficient supporting to the floodwall, the slabs are put a half meter down into the reserved groove on the waterside of the foundation.

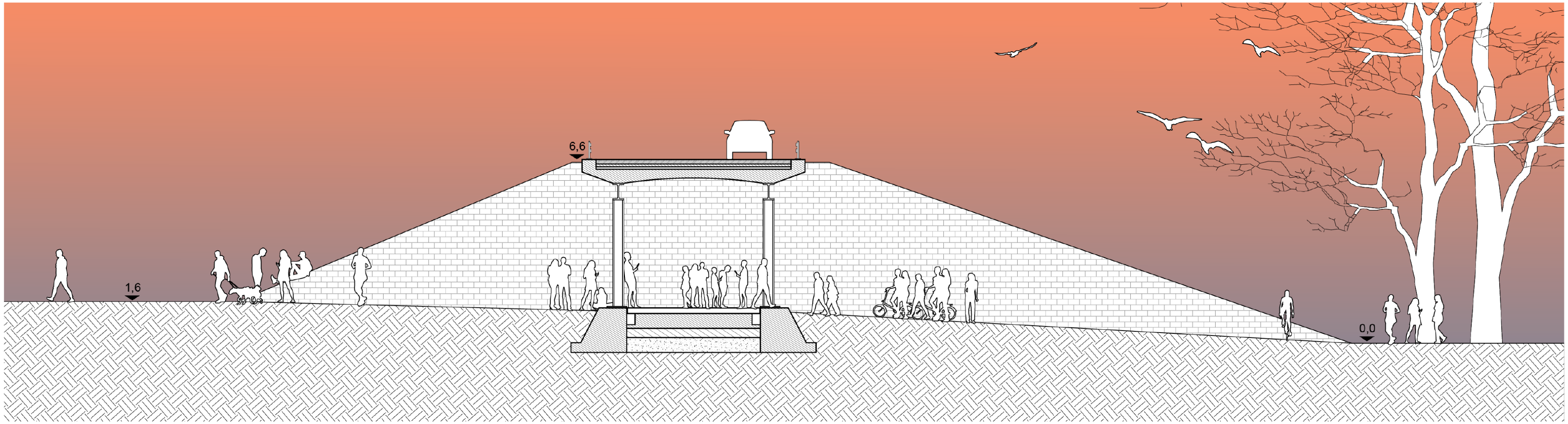
Regarding the selection criteria, the concrete slabs and the foundation are the water-retaining elements and supporting element respectively. The transition between the slabs and the foundation is the 0.5m deep groove. Moreover, In order to prevent leaking in between the slabs and non-closure, those slabs need to be placed on a straight line and covered with plastic membrane from outside. After that, piping is avoidable as far as the foundation is constructed properly and deep enough. However, based on my current knowledge about hydraulic engineering, it is not predictable if the vibration of the slabs weaken the whole defence system, therefore this term in the criteria was not considered to be achieved. Still, the design of modular & moveable floodwall has met most of the selection criteria, therefore its stability has been confirmed.

Figure 4.3.8
The ‘stop-log dike’ (Kent, 2020)

Figure 4.3.9
Samples of the concrete slab with metal edge ("Stelcon bedrijfsterrein producten - Stelcon", 2020)

Figure 4.3.10
Samples of the concrete slab ("Koop voordelig uw betonplaten bij Totaal Bestrating!", 2020)

Opening in summer for ventilation



Standing up when flood comes

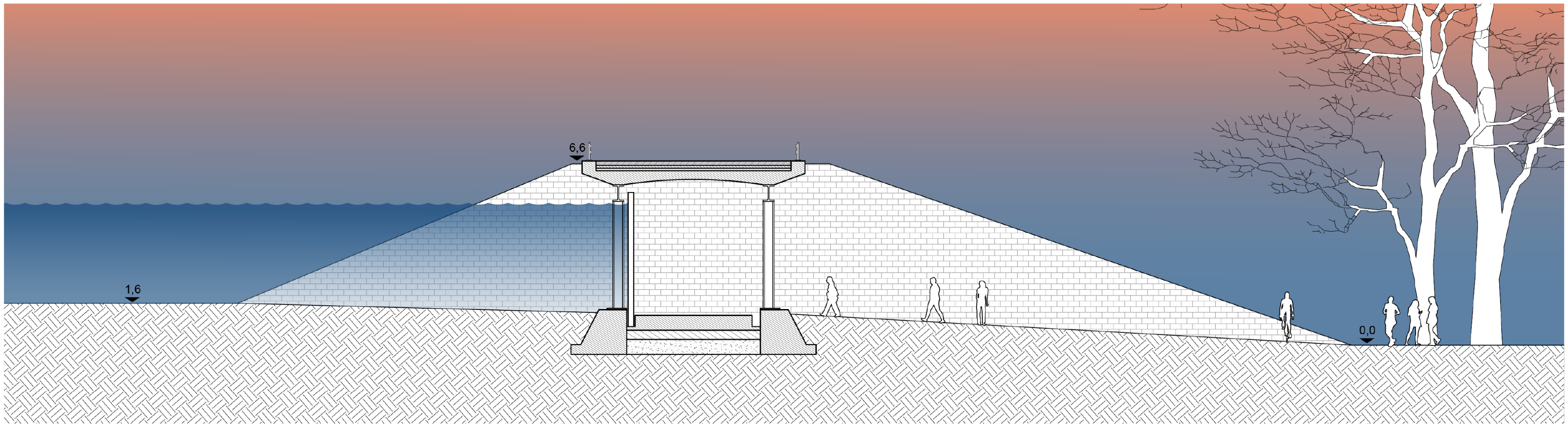


Figure 4.3.11 Technical sections of the modular & moveable floodwall in the dry season and during a flood event

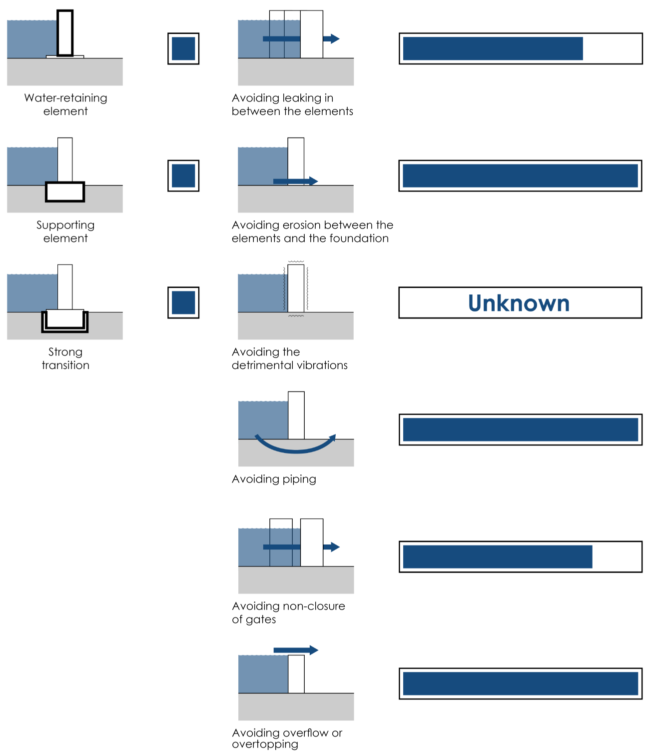


Figure 4.3.12 Assessment of the modular & moveable floodwall according to the selection criteria

4.3.4 Technical design of the rotatable portadam

Unlike the semi-permanent portadam, the rotatable portadam is a permanent construction. The rotation is achieved by the shaft that is installed on the concrete foundation. In order to achieve the defence height of 6m when the structure rotates down, the 'canopy' made of steel needs to be 9m wide. In order to achieve an intact closure, those rotatable portadams need to be placed next to each other on a straight line,.

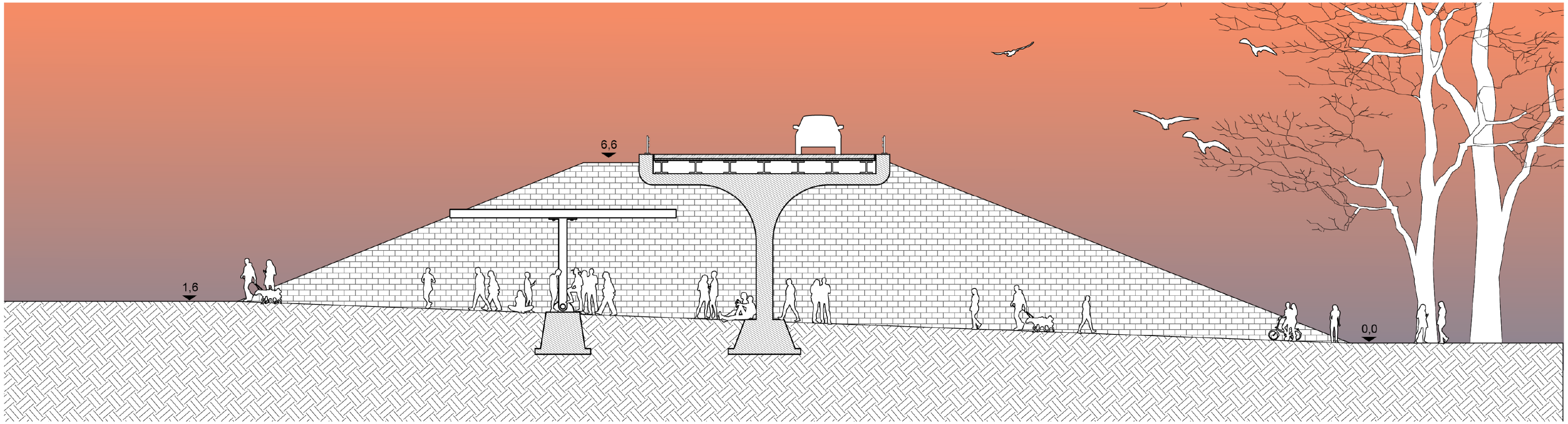
To avoid the conflict between the 'canopies' and the bridge pillars, a distance between the rotatable portadam and the bridge is inevitable. For that reason, the rotatable portadams and the bridge have to be separate elements which need own foundations.

After the structure is rotated down, the former 'canopy' becomes the water-retaining element, and the pillar and the concrete foundation together become the supporting element. Theoretically, their triangle relationship increases the strength and stability of the flood defence structure. However, the transition between the water-retaining elements and the subsoil is weak during a flood. The erosion might happen at the place where the water-retaining elements land directly on the grassland.

In addition, when the water-retaining elements are rotated down, the places where they land on might not be completely flat. It results in different angles of those steel plates, which leads to a risk of leaking in between those plates. Moreover, at the place where the rotatable portadam meets the profile of the original dike, a non-closed gap might appear.

Unfortunately, similar rotatable flood defence structures were not found in practice. To sum up, the stability of rotatable portadam was considered to be problematic.

Pavilion stands in summer for ventilation and provide shading



Put the pavilion down as defence element when flood comes

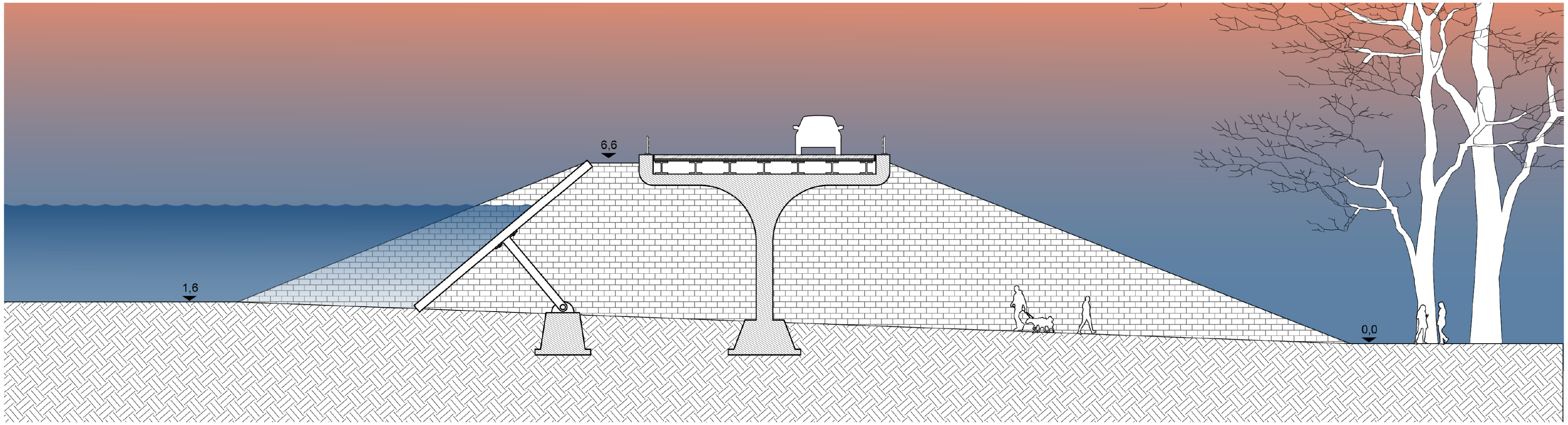


Figure 4.3.13 Technical sections of the rotatable portadam in the dry season and during a flood event

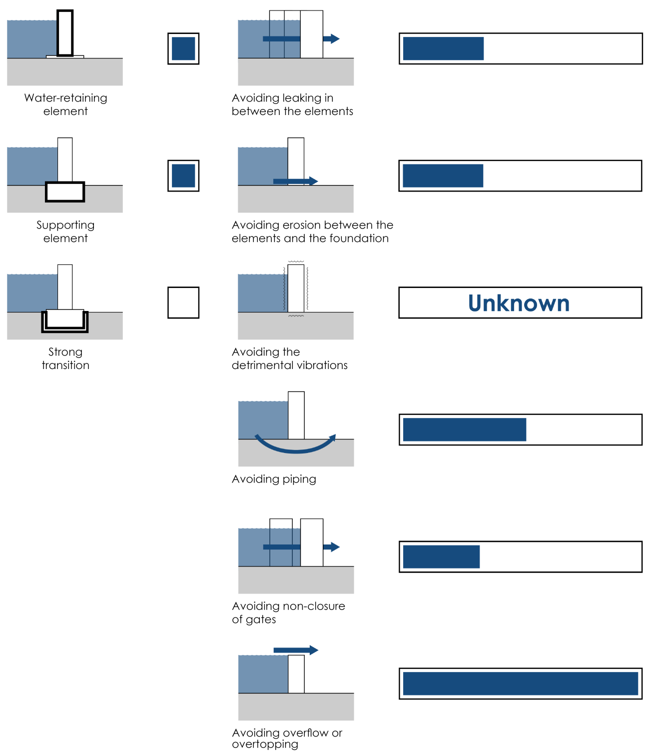


Figure 4.3.14 Assessment of the rotatable portadam according to the selection criteria

4.3.5 Technical design of the gabion dike

Sandbags are very useful to construct barriers for flood defence and other purposes (Thomson, 2011). However, they are usually used during emergency as the last defence line between flood and property, because their stability and strength are almost unpredictable. And limited study have been done about this temporary defence measure (Reeve & Badr, 2003).

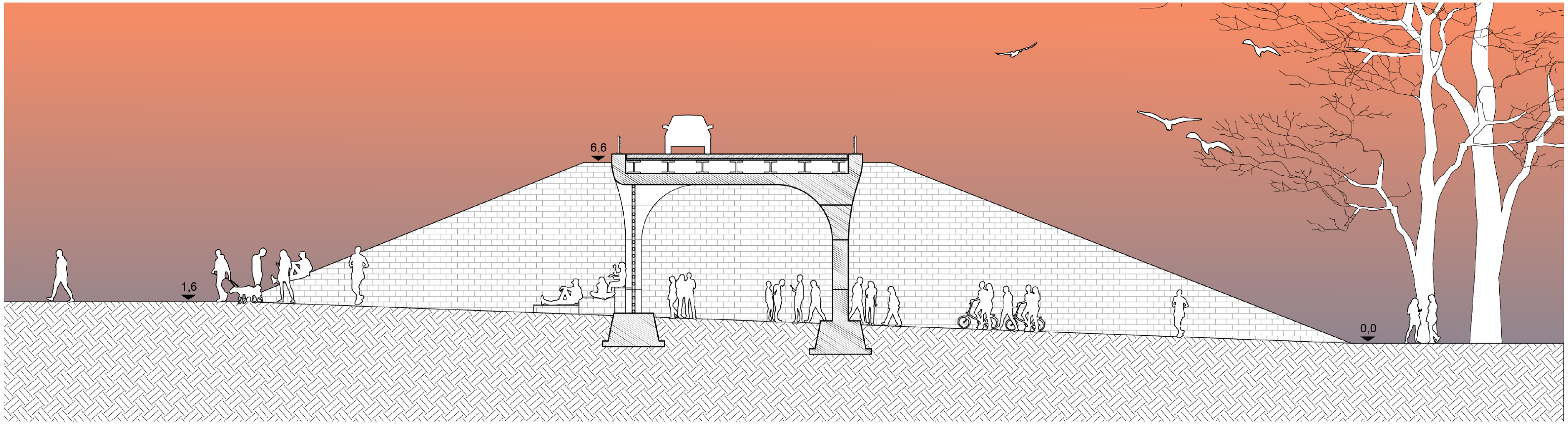
Sandbags are normally made from plastic or hessian membrane and filled in with sand or other particles. The advantage of the sandbag barrier is easy to build. But the traditional sandbag wall is formed with individual units without any connections or frameworks, which results in limited stability (Thomson, 2011). In order to enhance the stability of a sandbag wall, some measures have been invented. For example, the barbed wires or the spiked plates to be placed between layers of sandbags, or the straps and strands to tie the 'wall' up and hold sandbags together. Those measures bring up the stability to some extents, but meanwhile, complicate the operation and slower the responding speed (Thomson, 2011).

On the other hand, in Europe, the gabion structure has been used as the retaining wall and the hydraulic construction for a long time, but mainly for preventing erosions and reinforcing water banks as part of permanent constructions. Very few practice can be found in temporary flood defence. One of the temporary flood defence products I found on the market is a variant of the gabion wall, which is a foldable net filled in with sand on site (Figure 4.3.18). Comparing to the traditional sandbag wall, the gabion-like sand wall requires less time and effort to build, but is much more stable (Biggar & Masala, 1998).

In the technical design, I combined the advantages of a gabion wall and a sandbag wall. Two parallel walls made of metal grids are installed on the bearing structure of the bridge, which in between forms a cavity under the bridge. In wet seasons, the cavity is filled in with sandbags, which makes the under-bridge space inaccessible. Meanwhile, the gabion walls are functioning as a frame to hold the sandbags and transfer their loads to the bridge body and the ground. The defence height of the gabion dike is adjustable by controlling the number of sandbags.

Regarding the selection criteria, the sandbag wall is the water-retaining element, which is supported by the gabion walls and the bridge foundations.

Opening in summer for ventilation



Filling in sand bags when flood comes

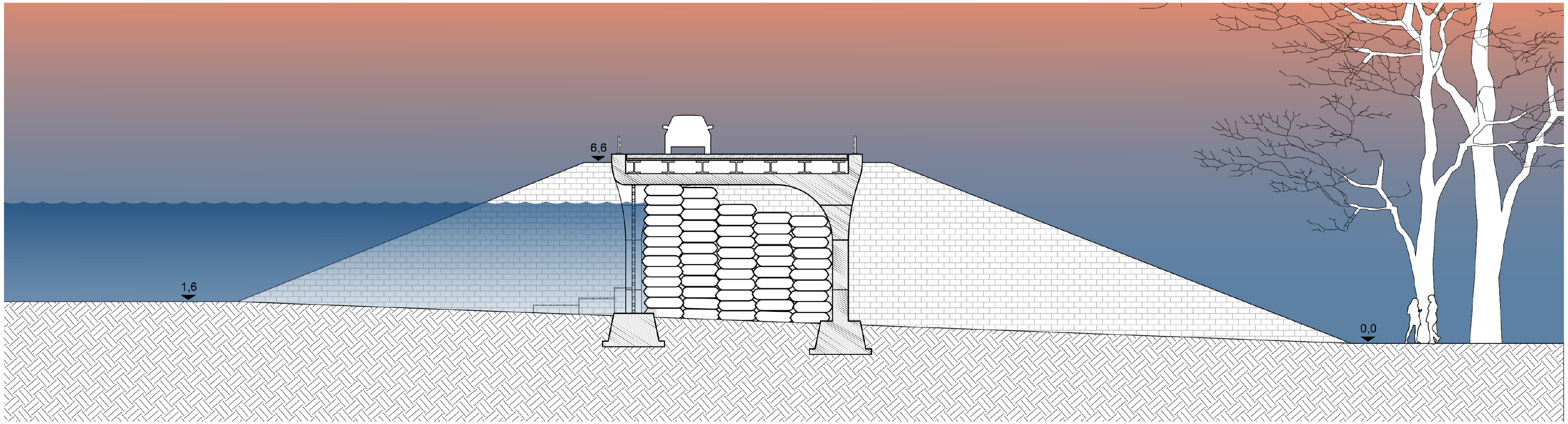


Figure 4.3.15 Technical sections of the gabion dike in the dry season and during a flood event

The transition to the ground is stable as long as the bridge structure is stable. However, even though the strength of the sandbag wall is enhanced by the gabion 'cage', there is still a risk of leaking from the gaps between sandbags. Since the height of sandbag wall is adjustable, the overflow of flood defence element is avoidable. In conclusion, the stability of the gabion dike filled with sandbags was confirmed.

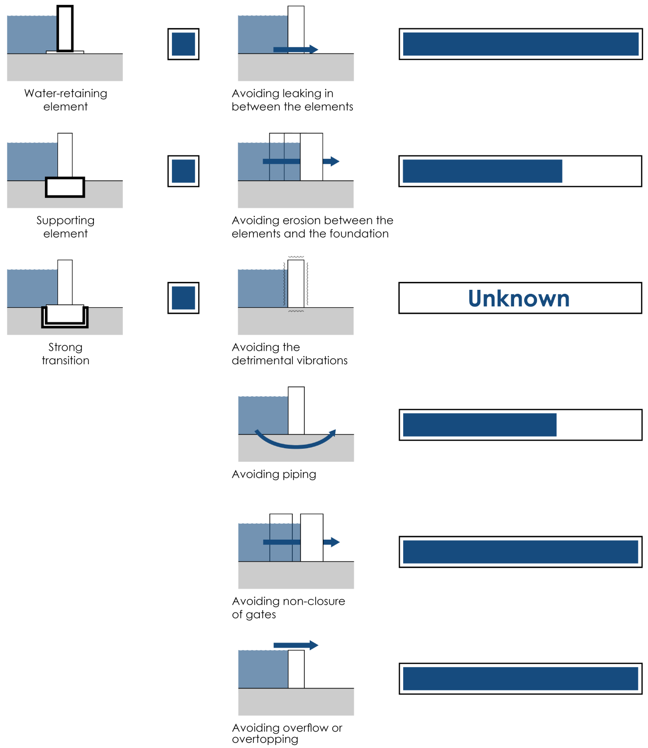


Figure 4.3.16 Assessment of the gabion dike according to the selection criteria

Figure 4.3.17
Traditional sandbag wall

Figure 4.3.18
Hesco concertainer installation: Stretching the cage (Biggar & Masala, 1998)

4.3.6 Selection of stable structures

In the research through design process, until the selection of the most stable flood defence structures, the design loop about structural stability has been concluded. The outcomes of Design Loop 2 together with the eight concept models from Design Loop 1 have finally answered the SRQ2: **How can the adjustable dike structure optimize the flow of a cool breeze?**

According to the criteria, the selection has been made. In the technical design of the inflatable dike partition, the modular & moveable floodwall and the gabion dike, the three crucial elements were identified and assessed to be strong, while in the design of rotatable portadam, the transition between the water-retaining elements and the subsoil is not as reassuring as the others. Meanwhile, the inflatable dike partition scored the highest in the criteria of avoiding potential failure mechanisms, followed by the modular & moveable floodwall and the gabion dike. Conversely, the rotatable portadam is an innovative structure, its stability hasn't been tested by practice. And technically, it has the risk of leaking in between and under the water-retaining elements.

As the conclusion, **the inflatable dike partition, the modular & moveable floodwall** and **the gabion dike** were selected as the most promising structures to be applied in the next phase: explorative site design, in order to explore their potential for social functions.

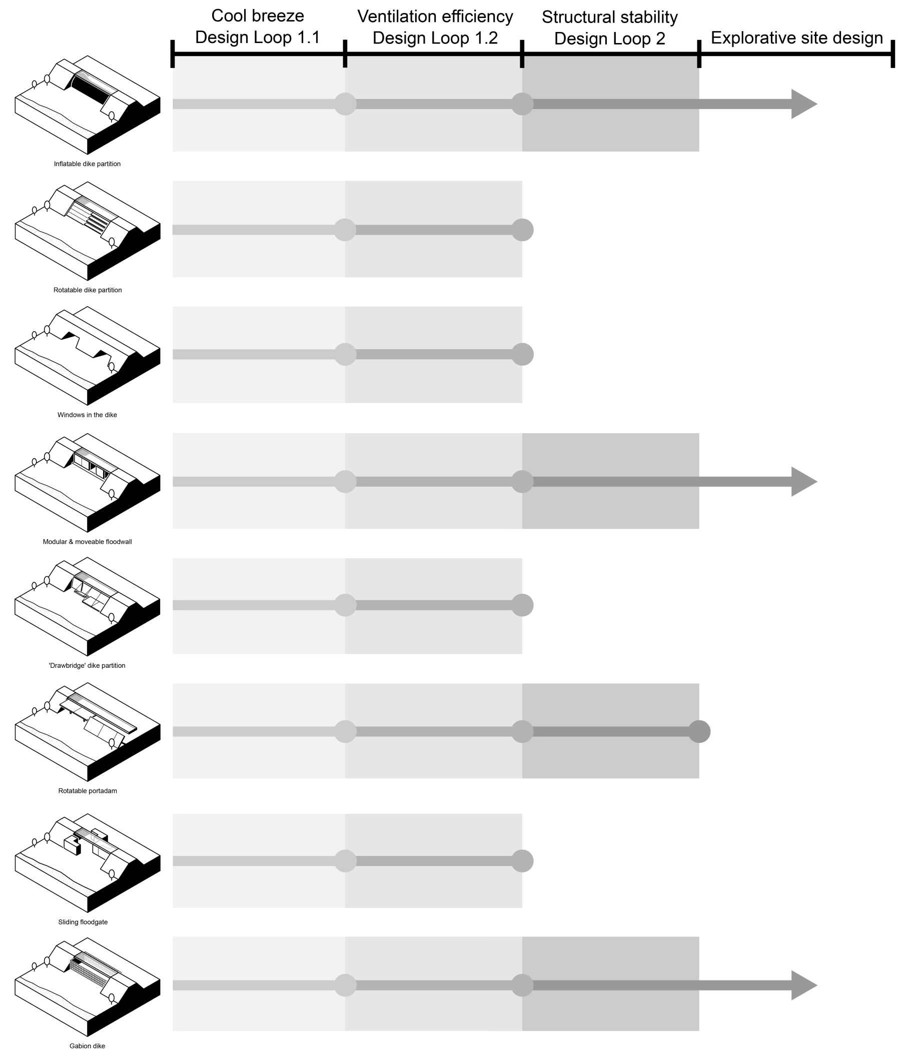
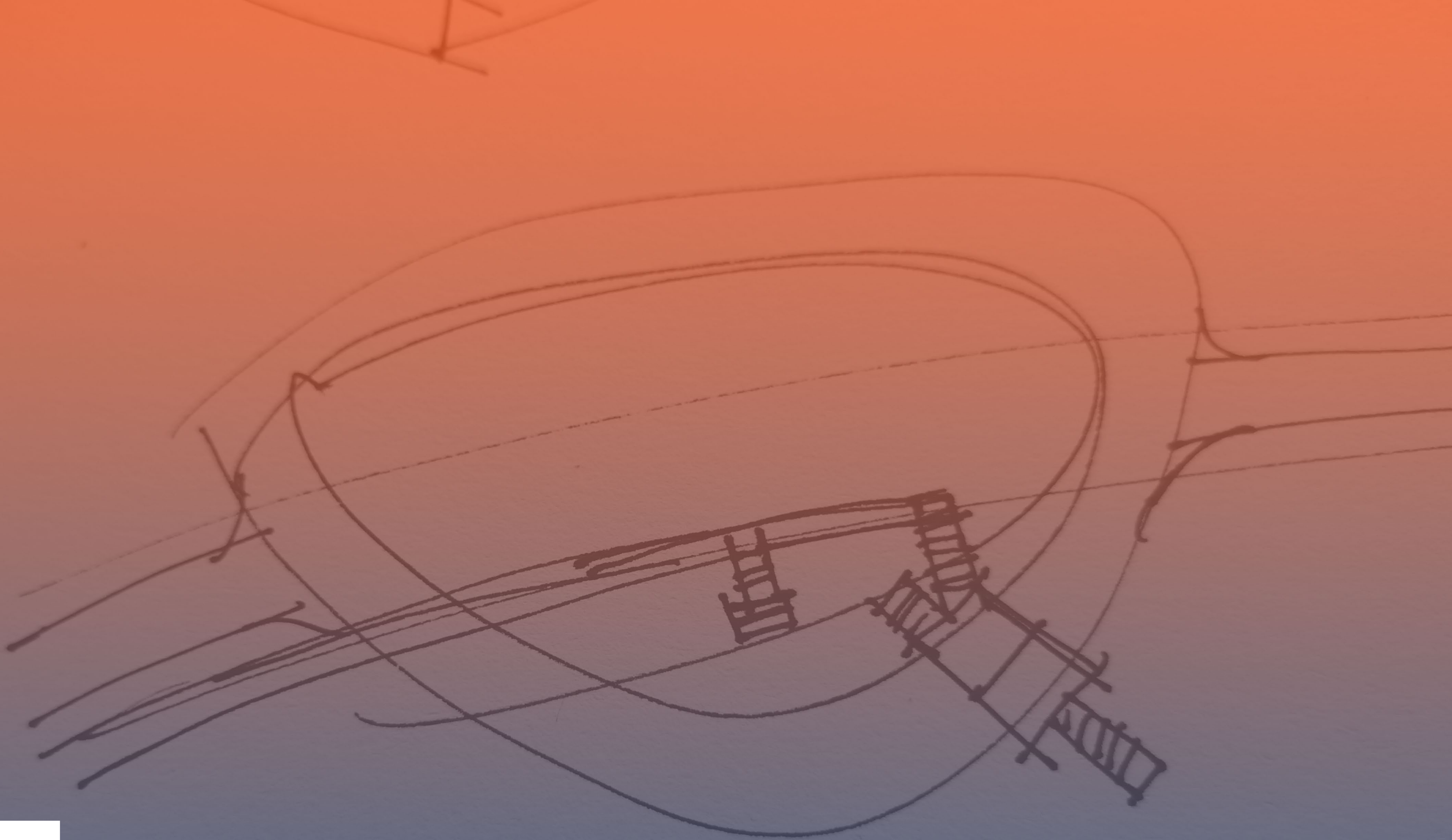


Figure 4.3.19 Overview of selection results until the end of DL2



5 Explorative site design

5.1 Introduction

In the last phase, I explored what multifunctions can be integrated into the three new flood defence structures on the site design level, regarding the relationship with the landscape context, adjacent the neighbourhoods and the composition of target groups.

Firstly, all possible multifunctions were proposed and linked to one of the three adjustable dike structures, according to the characteristics of the spaces they tend to formulate. Secondly, those multifunctions were assessed by relating them to their user groups. Eventually, I zoomed in to each site design to elaborate what space they shape and what programs they could carry.

In order to present the designs in an understandable way, masterplans from the top was considered to be not suitable anymore to elaborate the designs, since the design mainly takes place in a linear and vertical space which is covered by the bridge. The isometric diagram was chosen to be the way to visualize the site design throughout different time periods. On top of that, collages and renderings were made to show the activities and the designed atmospheres.

5.2 Potential multifunctions

Firstly, the double-lane road on the crest of IJsseldijk with two exits into the neighbourhoods should be preserved in the new site design.

Secondly, the bridge provides a shaded and protected space from solar radiation and precipitation, together with a proper use of the concrete slabs, the gabion walls and the rubber membrane, it is able to create enclosure spaces for various activities with unique landscape experiences (Whyte, 1980).

5.2.1 Multifunctions of the inflatable dike partition

The rubber membrane is a robust material with adjustability and flexibility, which makes it suitable to create space with unique characteristics to serve multifunctions. As mentioned in chapter two and the former part in this chapter, the flood defence function and shared-use of a road should be protected. After that, the other potential programs are elaborated below.

Trampoline

The rubber membrane, when it gets pumped to the certain height, can be framed into different shapes with the help of moveable light frameworks. The framed rubber bladder can be used as a springy trampoline or a so-called 'fundazzle' for kids to play on.

Slackline / Children playground

When the rubber dike is completely hidden under the ground, the space under the bridge can be modified into a jungle children playground with moveable hanging structures, such as swings, zip-lines and climbing nets. Not only for children, the under-bridge space can also be a place where young people hang out and play slackline.

Cafe / Bar / Meeting place

When the rubber dike is not operative, the space can be shifted into a relaxing zone with some moveable urban furniture. The bridge on top creates a dynamic space where people can experience both sunny and shading. With a mobile store, it can easily become a cafe bar where people meet and stay for a relaxing Sunday afternoon.

Swimming pool / Skating field / Dance floor

Technically, the foundation of rubber dike can be designed into any shapes as long as the width of rubber membrane is sufficient. If it is designed into the circle like a 'doughnut', it will formulate an enclosed space within the rubber 'doughnut'. The rubber partition is able to keep water outside, it can also hold water in the space it shaped. In summer, water can be filled into the 'doughnut' space that is created by pumping up the rubber bladder to the certain height, it temporarily becomes a swimming pool. It is similar to the inflatable swimming pool that people use in their backyards, but enlarged for many times. The use of a swimming pool doesn't need the rubber bladder to reach the full height, so it can be faster to get ready or away. In winter, when the rubber dike is activated for flood defence, the enclosure space in the rubber circle can be used for a temporary skating field. Besides that, it can also be used for a dance floor with a band playing in the middle and disco lights hanging from the bridge.

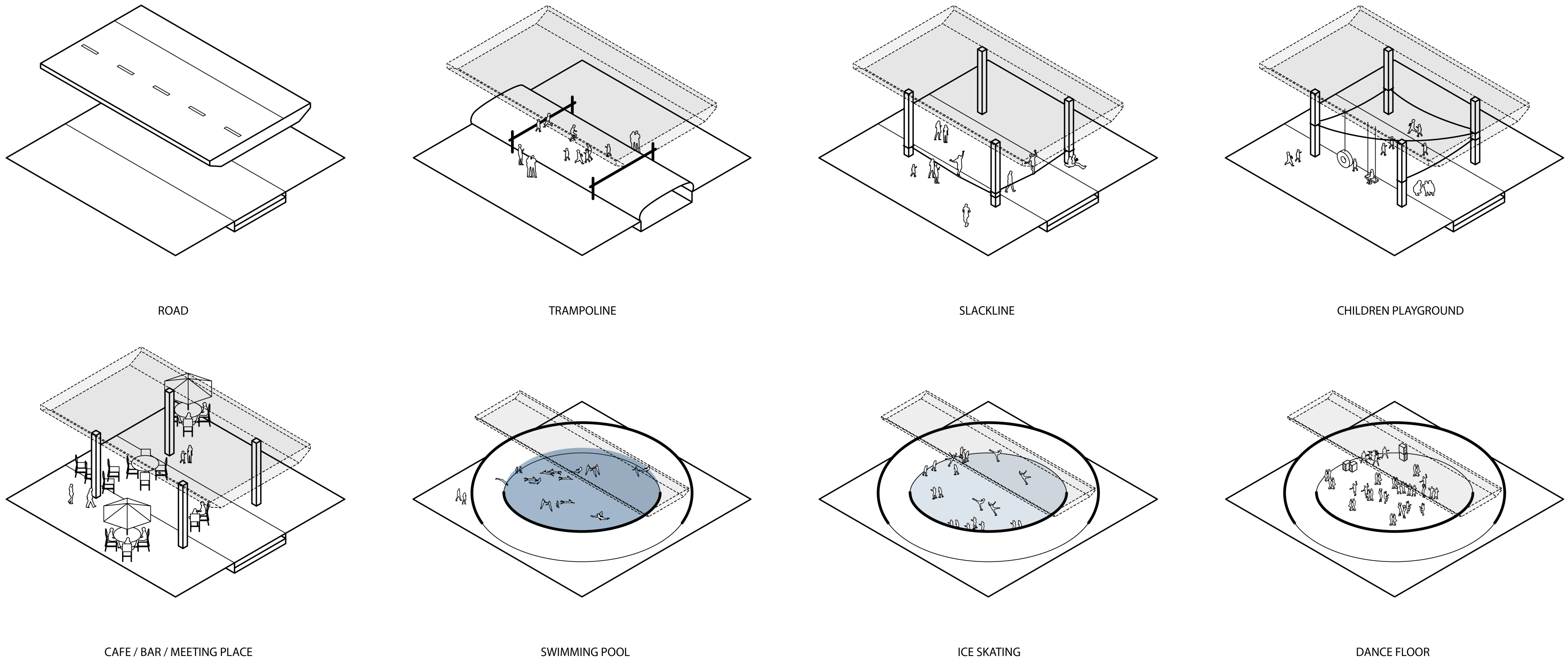


Figure 5.2.1 Overview of programs share space with the inflatable dike partition

5.2.2 Multifunctions of the modular & moveable floodwall

The precast concrete slab (5m*5m*0.2m) is designed for modularity and flexibility. They are water-retaining elements when they stand up together, but they can also be moveable partitions when rooms of certain shapes and sizes are demanded. By arranging these slabs in proper ways, different spaces are formulated. Besides, due to their modularity, the slabs are easy to be replaced if damage happens.

First of all, the road function is fulfilled on the bridge on top. After that, the other potential programs are elaborated below.

Cafe / Bar / Meeting place

When the floodwall is not needed, the space can be shifted into a semi-open room by placing the slabs on two directions which are parallel and perpendicular to the defence line. The space with unique landscape experience can be a cosy cafe during the daytime or a bar in the evening, once mobile stores and some moveable urban furniture are provided.

Market / Exhibition hall / Concert

Three pieces of the concrete slabs are able to formulate a small cell. The 'cell' is repeatable, which makes it suitable for temporary markets. During dry seasons, these modular spaces can even be a permanent market as long as the bridge provides the roof. Moreover, multiple standing slabs can create a linear space where exhibitions can be held. Sculptures, Installations, artworks and photographies all get a place to be displayed. Besides, four pieces of slabs can formulate a half-open space where a small scale concert can take place. Audiences can just stand and sit on the grassland, or use the provided moveable urban furniture.

Outdoor theatre

Two concrete slabs standing next to each other (10m*5m) will be a perfect projection wall. The new IJsseldijk can be a place for the active and sustainable outdoor theatre. Locals can grab a chair or just sit on the grass to enjoy a movie with a bottle of beer and a box of popcorn from the nearby mobile store.

Graffiti wall

After the new IJsseldijk is realized by applying the modular & moveable floodwall, it is unavoidable that some hippies will go there and use them for graffiti. Gradually, the spot has the potential to become a tourist attraction.

Climbing wall

The places where moveable floodwalls meet the preserved IJsseldijk can be the climbing zone. Climbing holds are installed on those slabs and the new concrete retaining wall at the profiles where IJsseldijk is removed.

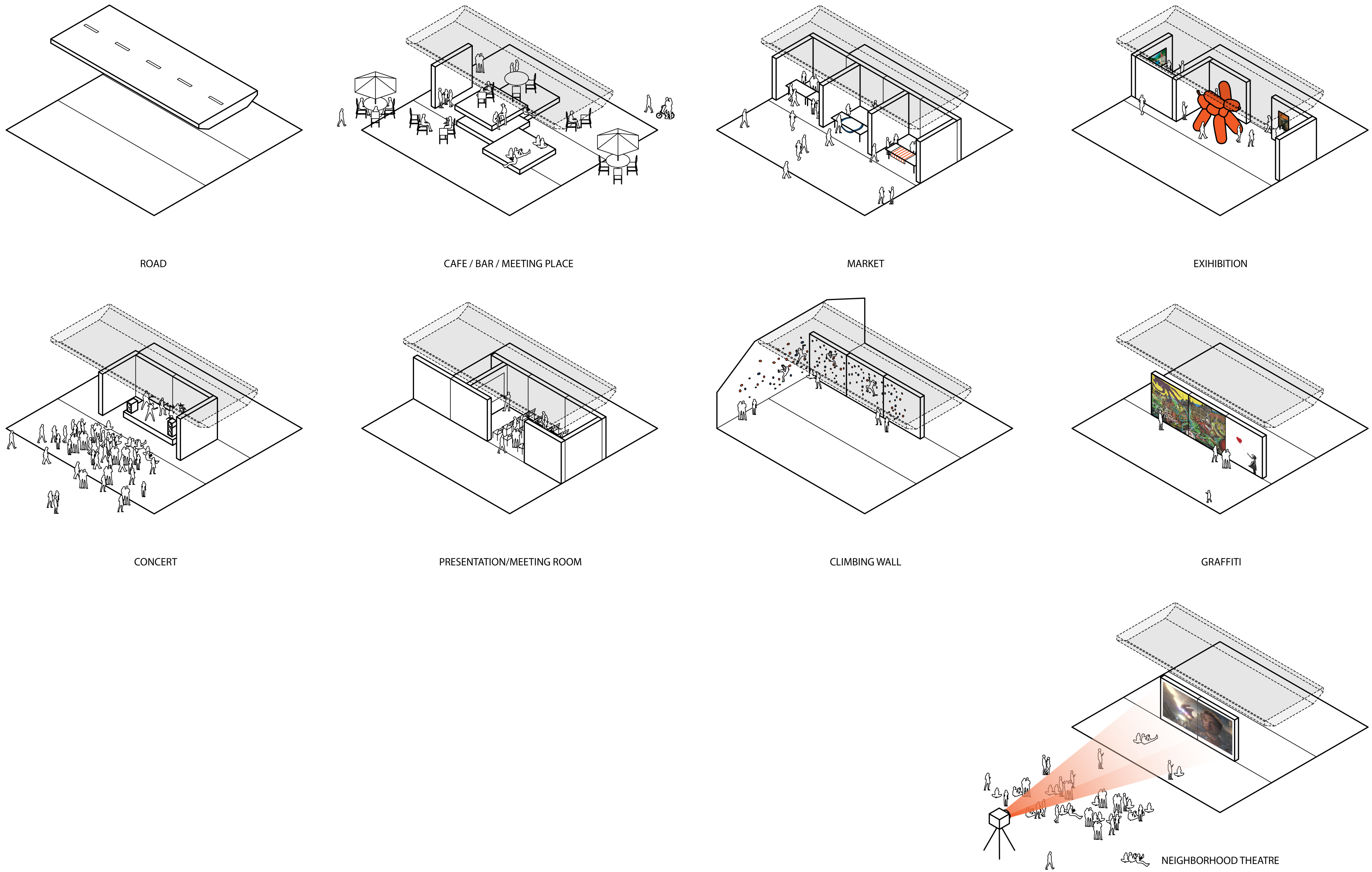


Figure 5.2.2 Overview of programs share space with the modular & moveable flood-wall

5.2.3 Multifunctions of the gabion dike

The wire-mesh gabion 'cage' may not be pleasant from the aesthetic perspective. But considering its flexibility and multifunctionality, it is believed to be worth. The characteristic of the gabion wall to hang objects on it. This feature has been utilized to the optimum in the explorative site design. First of all, the road function is fulfilled on the bridge on top. After that, the other potential programs are elaborated below.

Second-hand exchange

The most direct shared-use of the gabion is hanging things on it. The gabion wall can be a 'platform' for the second-hand clothes exchange amongst residents from the neighbourhoods. Gradually, not only people from the neighbourhoods but also from the city centre and elsewhere can come to the gabion dike with their unwanted clothes and other dressings to participate in the activity of circular economy and contribute to sustainability. The only additional equipment to fulfil this shared-use is the clothes hangers.

Children playground / Hammock / Slackline

Based on the idea of hanging objects on the gabion, the space between the gabion walls and under the bridge can be modified into a jungle playground with moveable hanging structures, such as swings, zip-lines and climbing nets. Besides, facilities like the sandpit and the seesaw, which are robust to sandbags, can also be placed. Moreover, other hanging elements for sports and recreation, such as slacklines and hammocks are also welcomed.

Climbing wall

At the places where the gabion wall meets the preserved IJsseldijk, the climbing zone can be established. Climbing holds are installed on two different types of back walls. The one is the new concrete retaining wall at the profiles where IJsseldijk is removed. The other is the penetrable gabion wall. At the climbing zone, the metal nets need to have a small grid (2cm*2cm) which climbers shall not directly climb on it.

Exhibition / Dance floor / Presentation room

The semi-open space under the bridge is also suitable to be an exhibition hall where sculptures, installations and photographies can be displayed. Additionally, the linear corridor-like space shaped by the gabion walls that people can look through has great potential to be the tunnel of light where massive dynamic and glowing bulbs shining on their own. The new IJsseldijk has the potential to become a tourist attraction like the Tunnel of Love in Rotterdam.

Moreover, Flexible rooms can be created and transformed from semi-open to private with the help of curtains that are hanged from the top of the gabion wall to the ground. The size of those rooms are adjustable by folding and unfolding those curtains. The rooms can be used for a presentation/meeting room, a dance floor or a small theatre.

Cafe / Bar / Meeting place

After sandbags are evacuated, the space can be shifted into a semi-open place where is suitable to be a cosy cafe during the daytime or a bar in the evening, once mobile stores and some moveable urban furniture are provided.

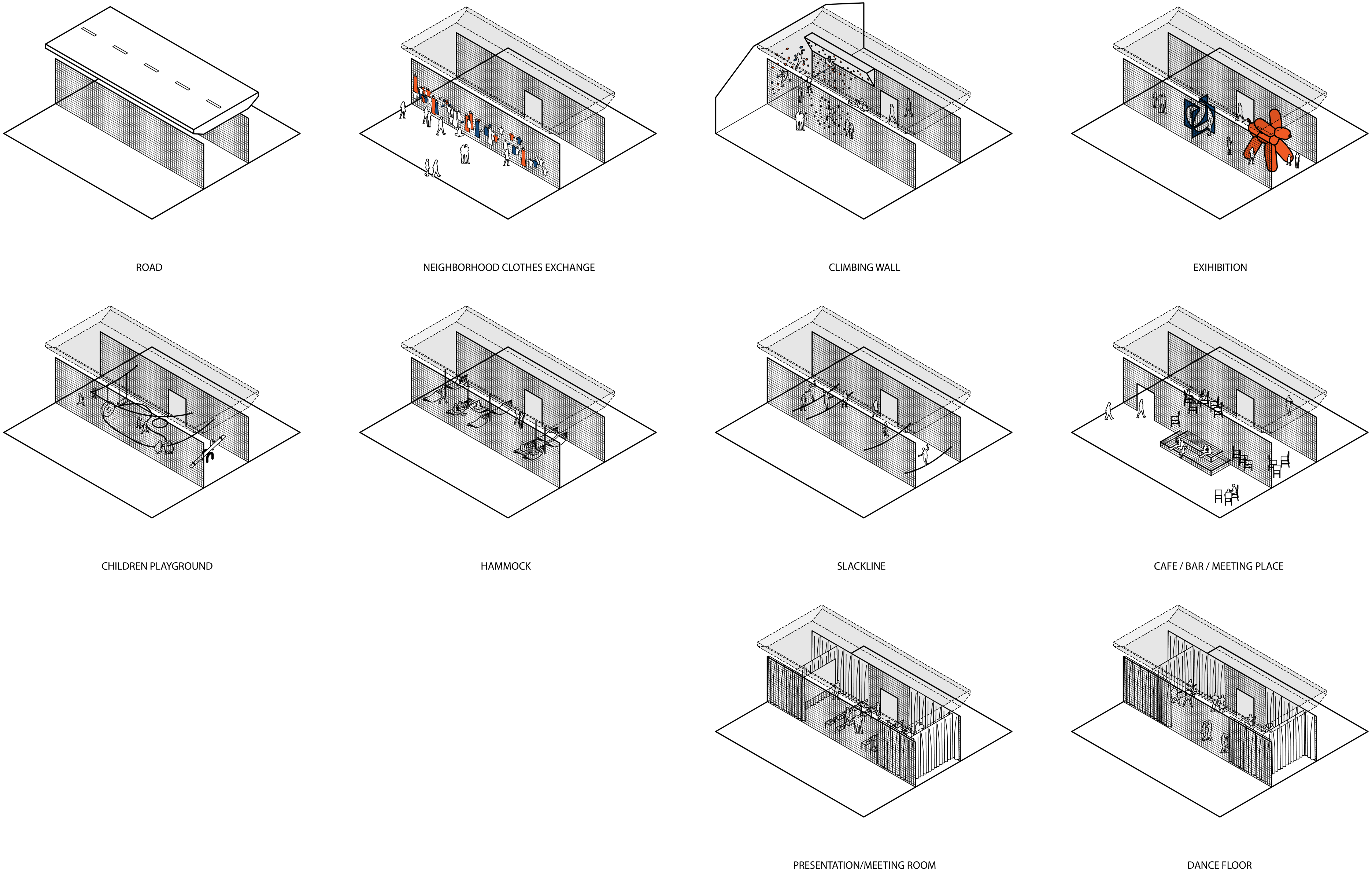


Figure 5.2.3 Overview of programs share space with the gabion dike

5.3 Summary of social functions

In general, the sheltered sitting/meeting places are suitable for the both three structures. Specifically, the gabion dike structure serves more multifunctions than the others, benefiting from the characteristic of hanging objects and its semi-open space. Besides, the moveable floodwalls were able to create flexible rooms. On the other hand, the rubber structure creates the activity space that is very unique. An overview of all possible multifunctions and their relationships with the three adjustable dike structures is presented (Figure 5.3.1).

In the former two design loops, the purpose of urban ventilation was targeting the adjacent neighbourhoods. However, the social multifunctions of defence space can be beyond that and doesn't necessarily only serve the local residents. The new types of multifunctional flood defence are also good attractions to people from Rotterdam city, Alexander district, and tourists from over the world. An overview of the relationship between the programs and their user groups is presented (Figure 5.3.2).

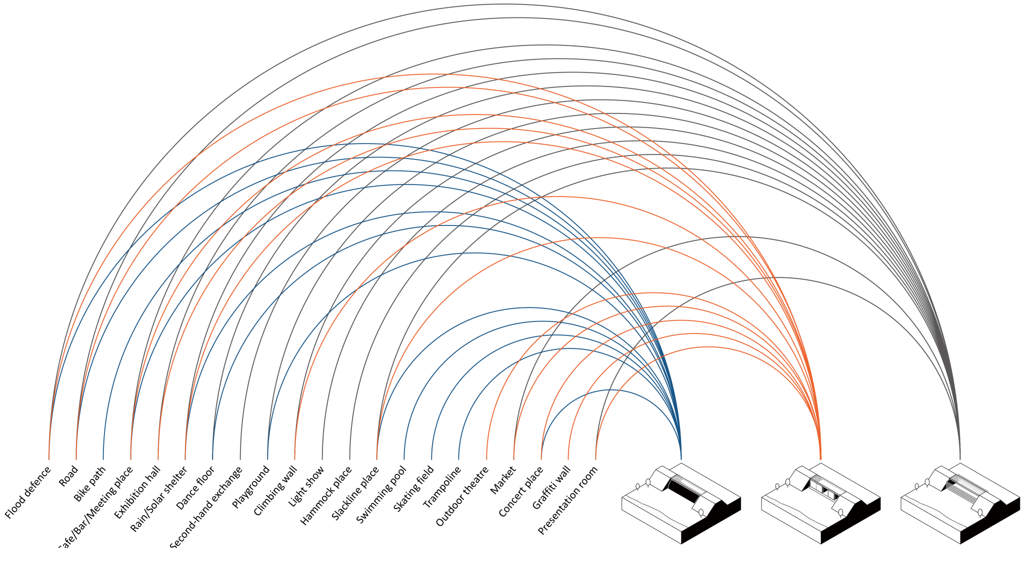


Figure 5.3.1 Overview of shared-uses link to the flood defence structures

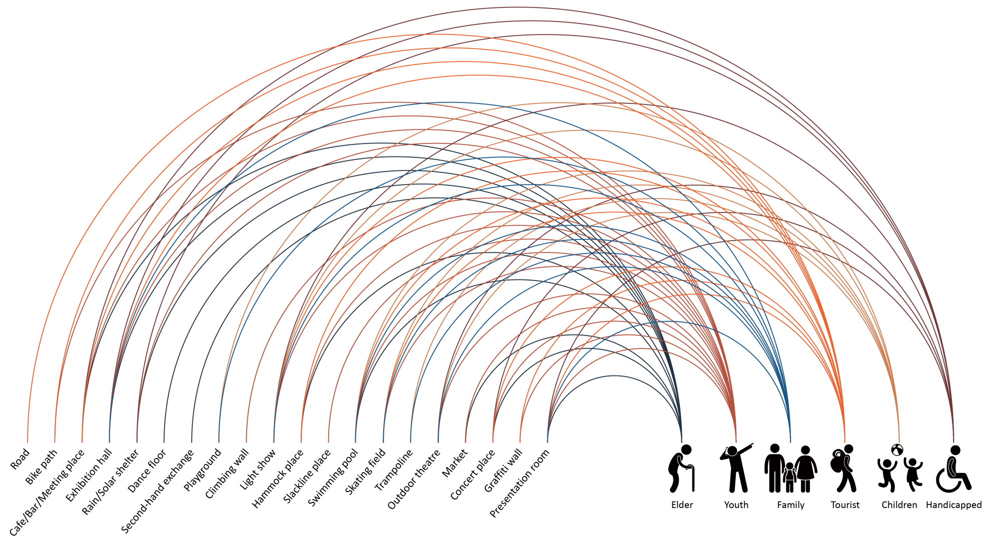


Figure 5.3.2 Overview of shared-uses link to their user groups

5.4 Site design

5.4.1 Site design of the inflatable dike partition

In wet seasons, the rubber bladder gets pumped and fills the cavity under the bridge to achieve flood protection. In dry seasons, the rubber membrane is hidden under the ground and covered with the metal grids at the ground level. So that the cool breeze and pedestrians can penetrate the flood defence line. The path system that goes from the rubber dike into the floodplain was designed.

The part of rubber dike that is in front of the neighbourhoods' open areas was designed into the 'doughnut' shape, which formulates the plaza for multiple activities in the middle. The plaza is hard-paved and three stairs down from the foundation of rubber dike. As mentioned earlier in this section, the rubber partition is able to keep water outside, it can also hold water in the space it shaped. The plaza with a well-designed water supply and drainage system can be used for a temporary rubber swimming pool when the rubber bladder is pumped up to 2m tall with the stored water from the reservoir. The depth of the rubber swimming pool was designed to be from 1.65m to 2m. On the south side of the plaza, the wooden bridge above the 2m rubber wall is connecting the ground and the water. In spite of the path to the swimming pool, another

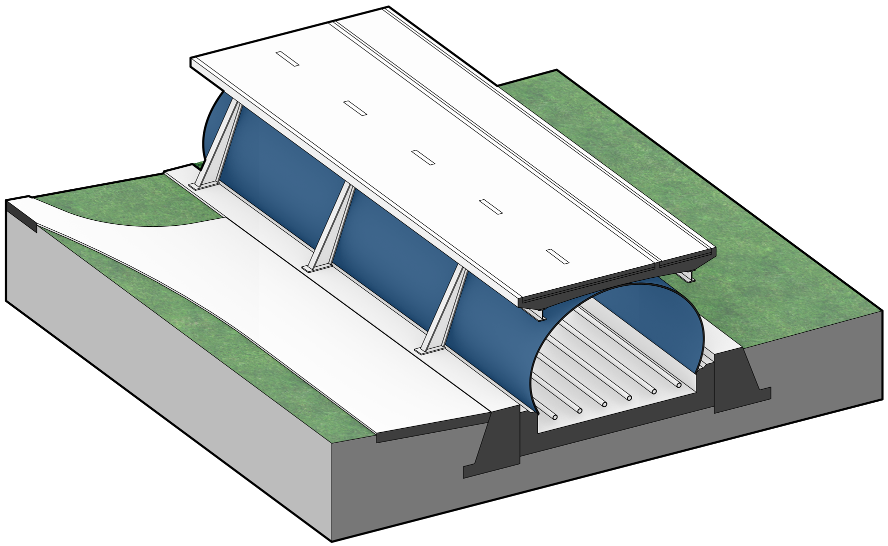


Figure 5.4.1 The standard section of the rubber dike in operation

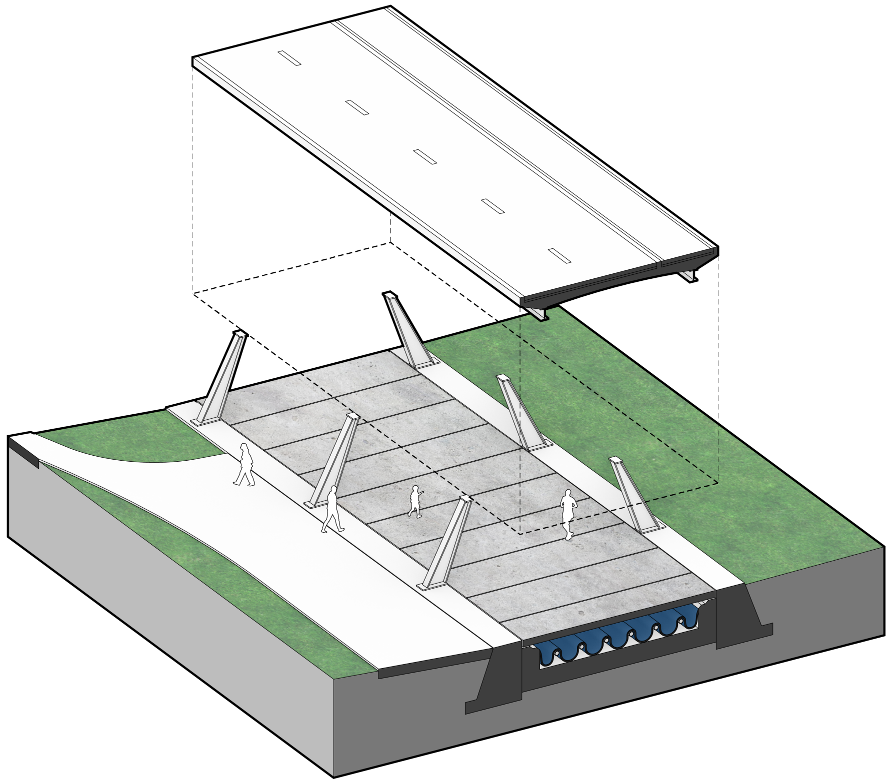


Figure 5.4.2 The standard section of the rubber dike out of operation

path from the bridge is going up to the same height as the car road and connecting to the elevated wooden path, which is parallel to the defence line. The other end of that wooden path lands on the crest of the original IJsseldijk in which is partly preserved and goes down to the floodplain with the wooden stairs on the dike slope. Above the swimming pool, the elevated path is connected to the water jumping platform where people can jump into the water from 2.8m.

However, 2m partition is not sufficient for flood defence, and the rubber dike will eventually need to go up to 5.5m and touch the bottom of the bridge deck. In order to avoid conflict between the wooden bridge and the rubber dike, the wooden bridge was designed according to the traditional Dutch drawing bridge which can open from the middle to almost 90 degrees.

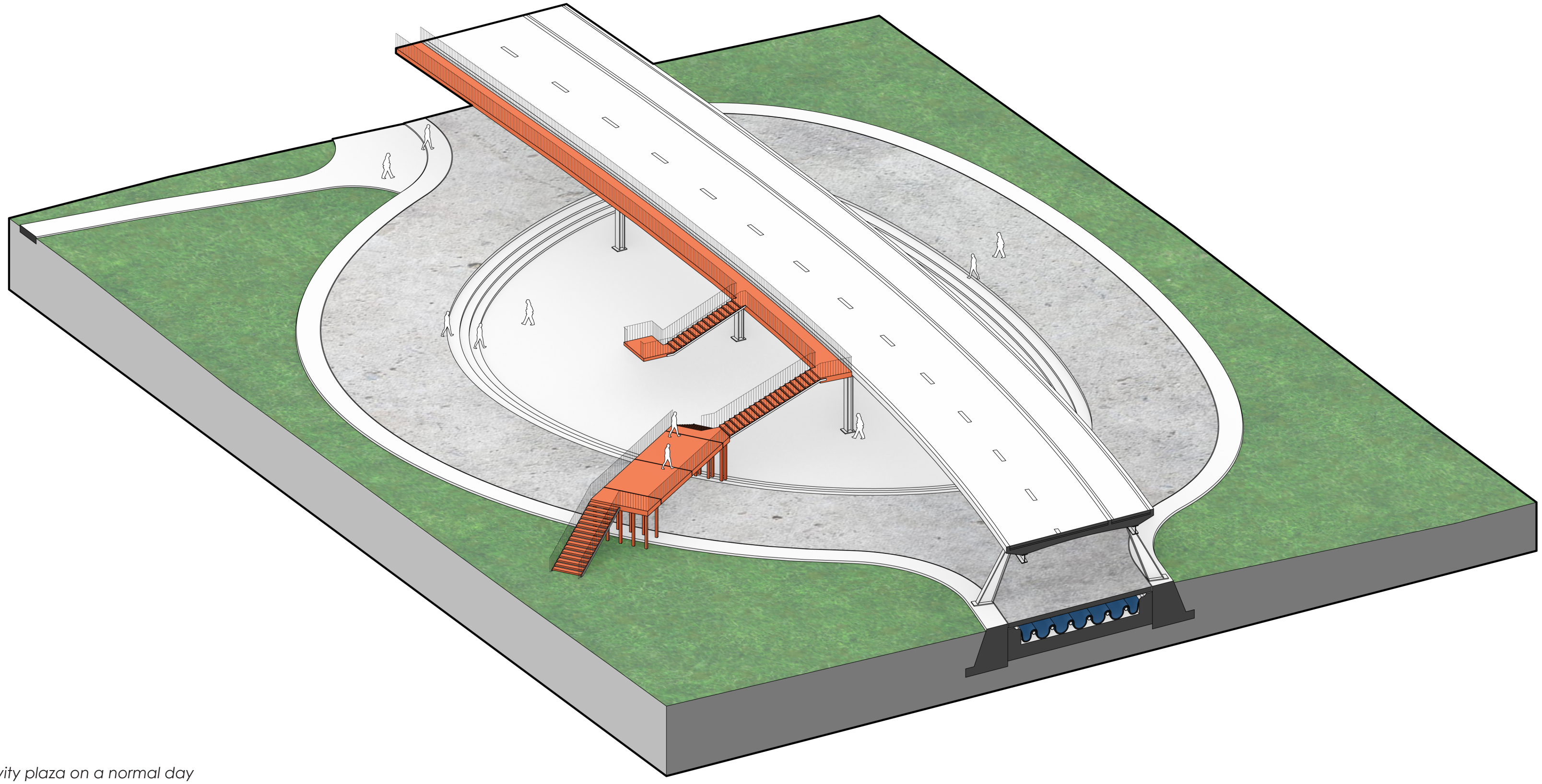


Figure 5.4.3 The activity plaza on a normal day

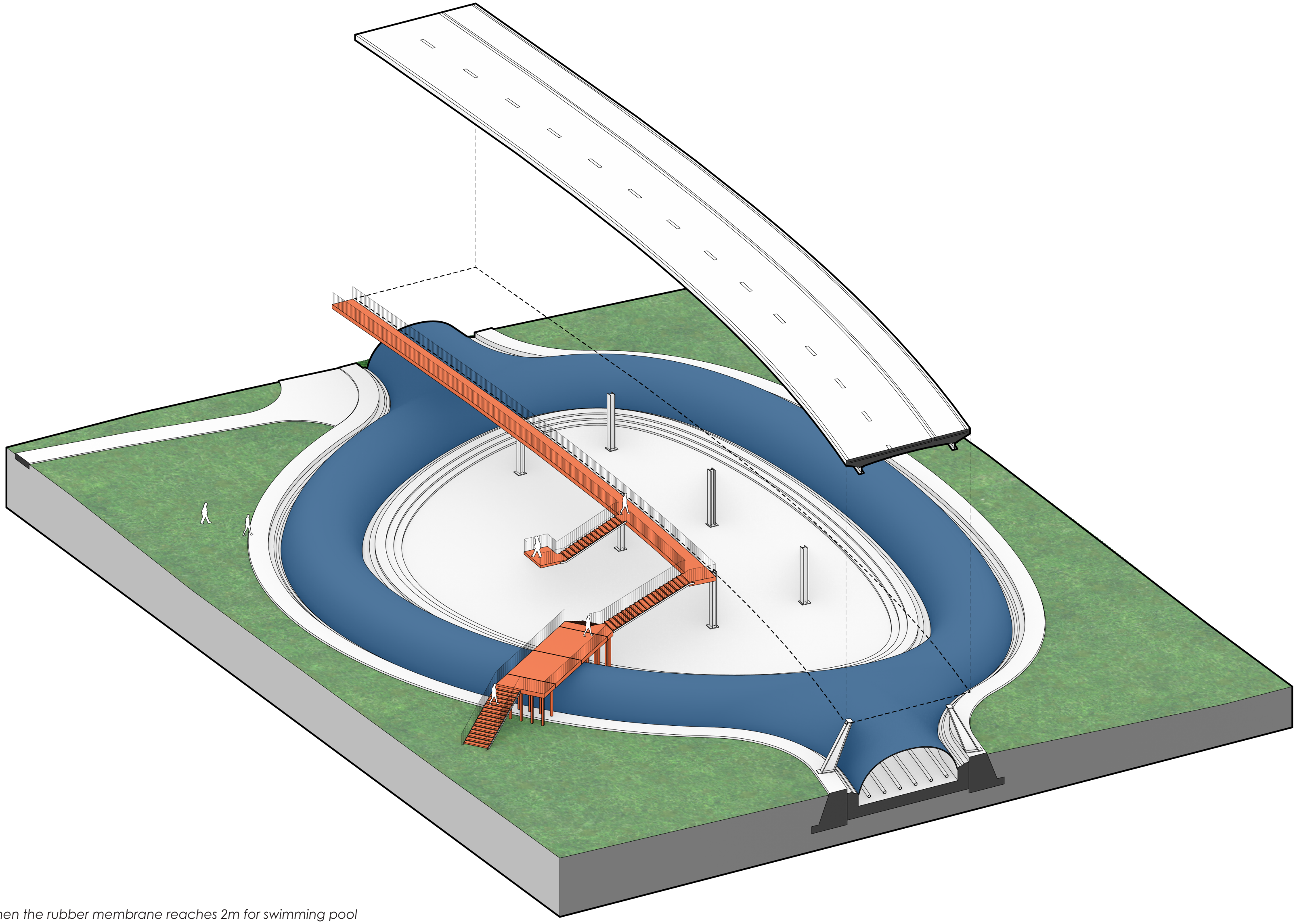


Figure 5.4.4
The activity plaza when the rubber membrane reaches 2m for swimming pool

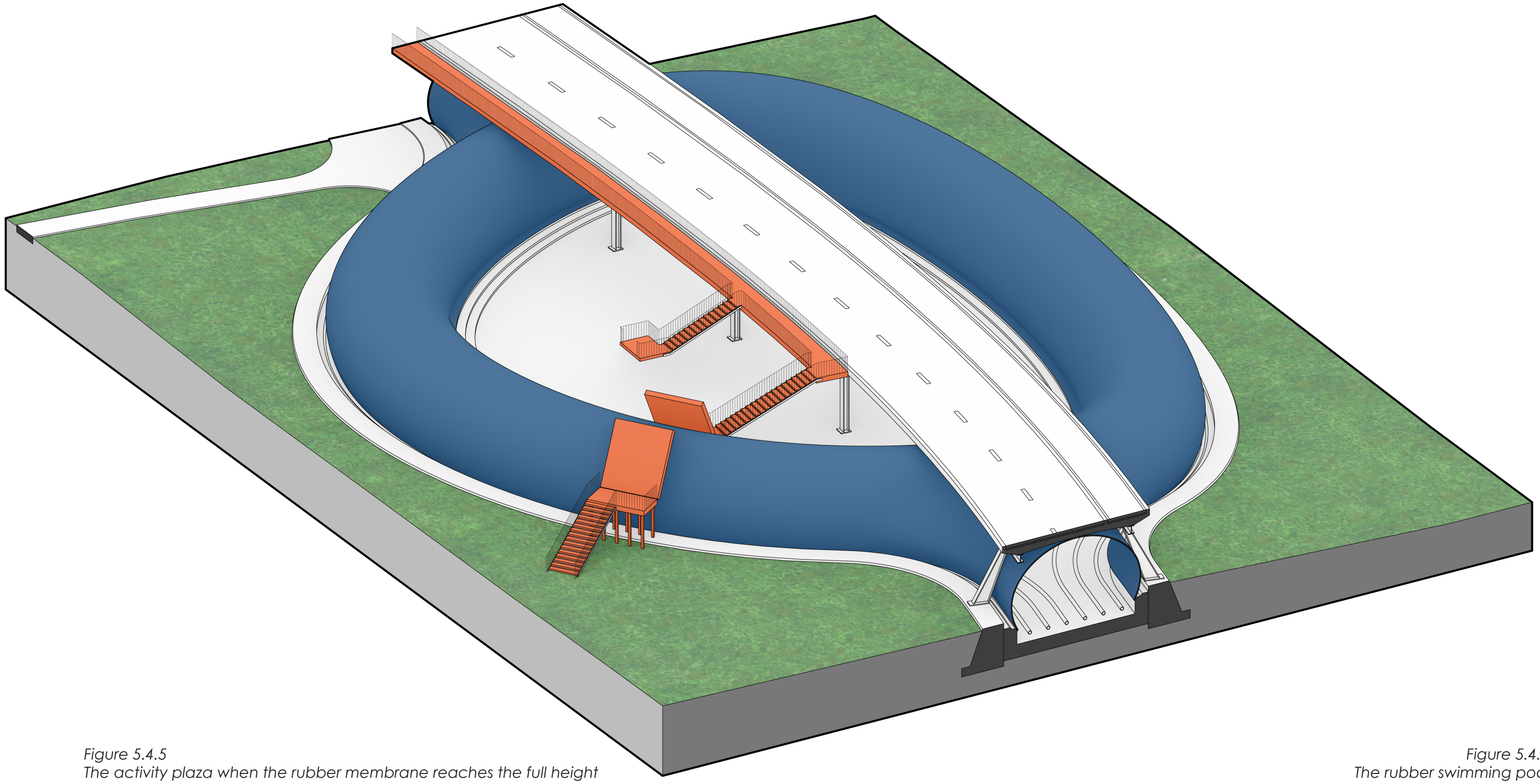


Figure 5.4.5
The activity plaza when the rubber membrane reaches the full height

Figure 5.4.6
The rubber swimming pool

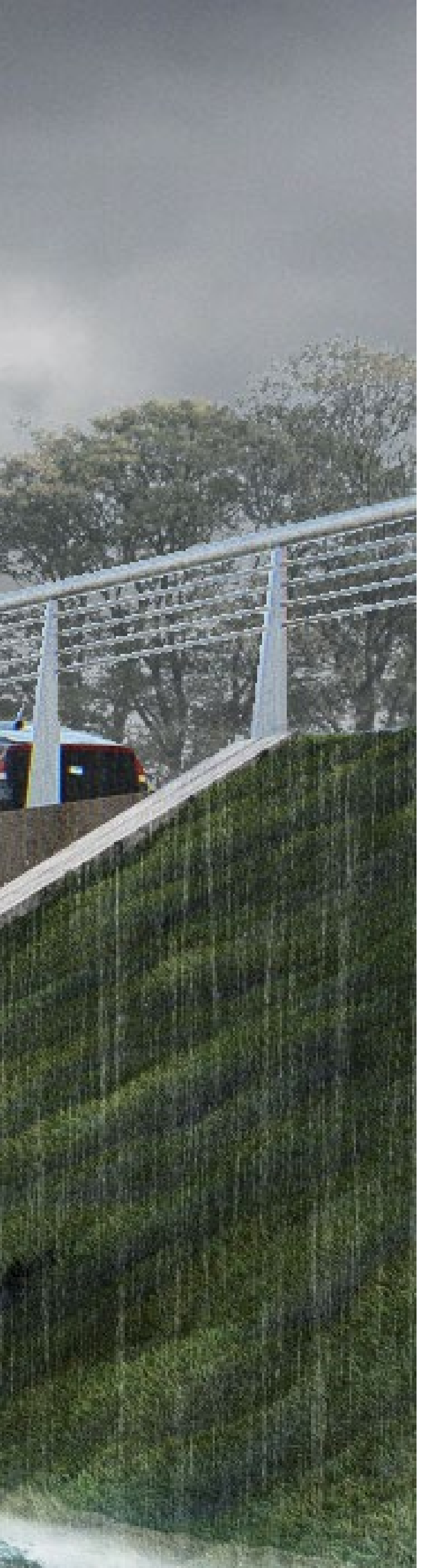


Figure 5.4.7
The inflatable dike partition operates during a flood

5.4.2 Site design of the modular & moveable floodwall

In wet seasons, all the concrete slabs get pulled up and stand next to each other on a straight line to form the floodwall. In practice, a plastic membrane can be used to cover them from the waterside in order to prevent seepage from the gap between two pieces (Biggar & Masala, 1998). In dry seasons, the surfaces of the lying slabs and the curbstones were designed to be at the ground level. So that the cool breeze and pedestrians can penetrate the flood defence line freely. As mentioned in the technical design section, in order to support those modular floodwalls, the half-metre deep grooves are precast on the concrete foundation. In spite of the grooves where they stand as the floodwall, the grooves are also reserved on the concrete foundation perpendicularly to the defence line at each 5m. These grooves were designed for slabs to divide the space.

The same elements are used to make the paved spaces and the pedestrian paths on the grass in a way to enhance the continuity and consistency of the landscape. The precast slab was found to be low-priced but very useful to define the landscape language and enrich the texture, at the same time to create the paved activity space for people who don't want to get in touch with bare soil and wet grass.

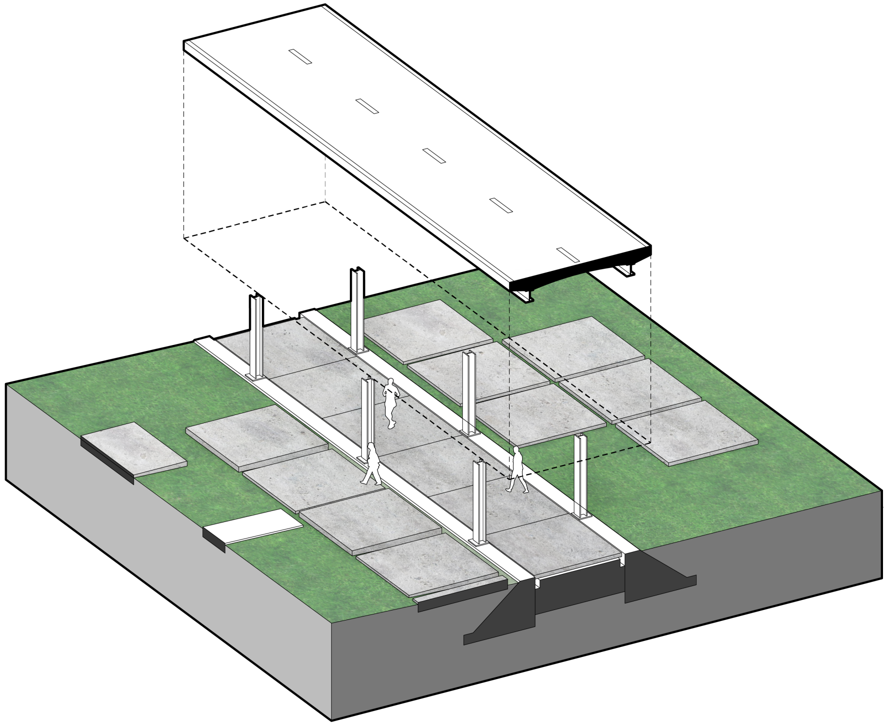


Figure 5.4.8
The standard section of the modular & moveable floodwall on a normal day

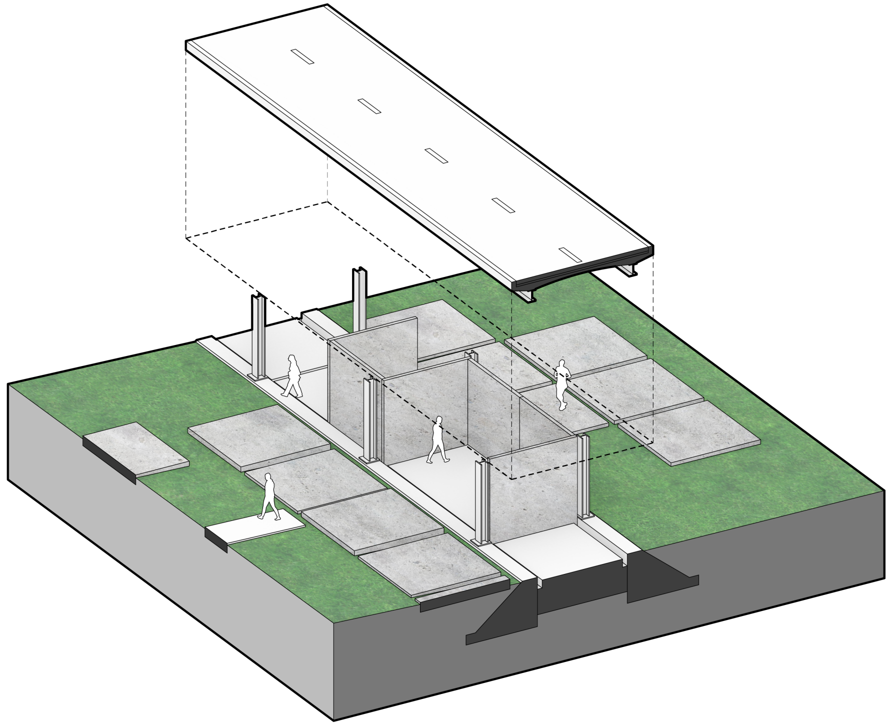


Figure 5.4.9
The standard section of the modular & moveable floodwall when activity space is needed

Figure 5.4.10
The exhibition space on a raining day


Mead
jelly

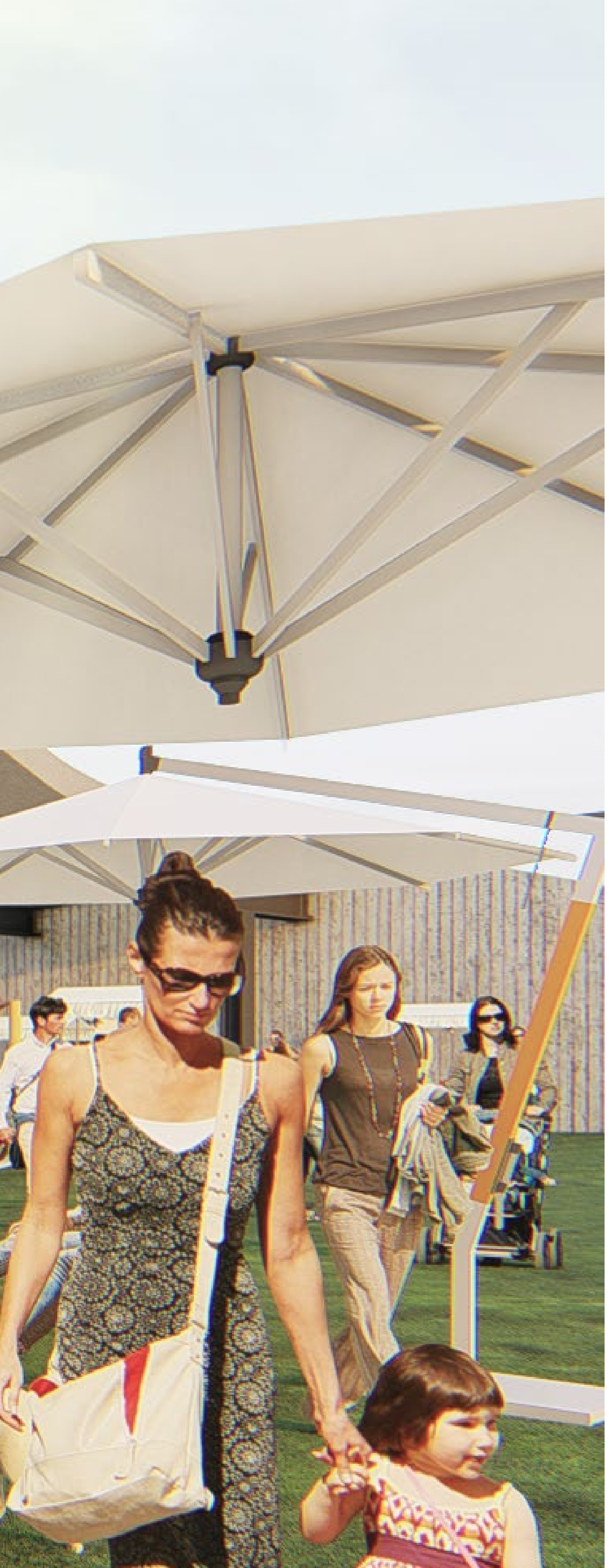


Figure 5.4.11
The open market

5.5.3 Site design the gabion dike

The wire-mesh gabion 'cage' may not be pleasant from the aesthetic perspective. In order to make them less striking, they are integrated into the bridge body by installing the metal wires on the bridge pillars. Correspondingly, the capability of holding sandbags is enhanced. Sliding gates made from the same material are placed in the gabion wall at a regular distance. Those gates are not only for pedestrians to access the under-bridge space and cross the dike, but also for sandbags to be carried in and out.

The annual Kralingseveer lighting festival takes place at the new IJsseldijk. The Kralingseveer lighting festival will be an event like the GLOW Eindhoven and a place like the tunnel of Love in Rotterdam where artists can let go of their creativity in a linear space. During the festival, various lighting designs, such as neons, lanterns and laser will be hanged on the gabion walls where people can also look through to the landscape, or from the ceilings.

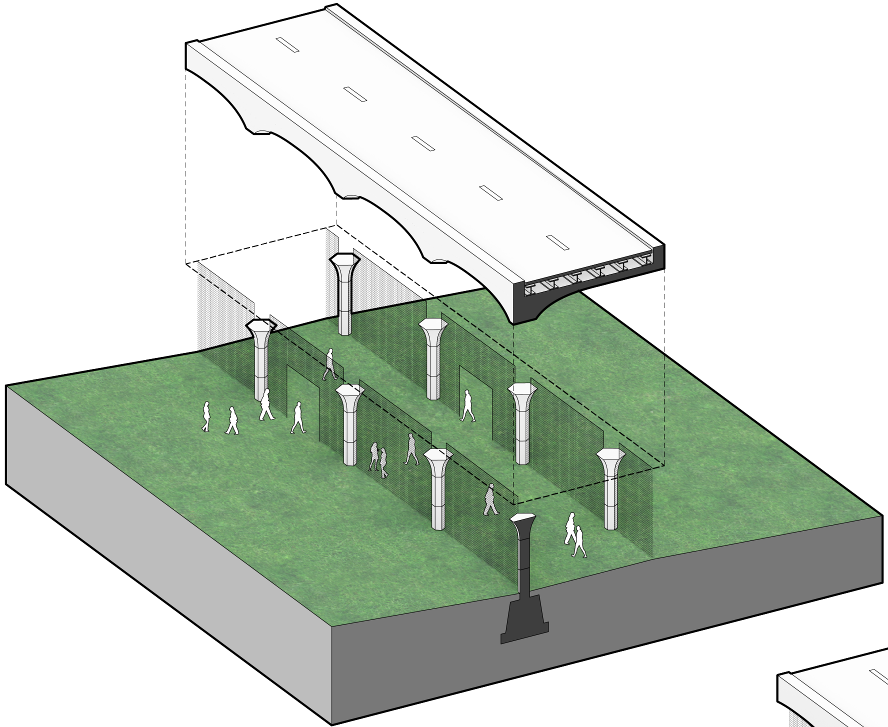


Figure 5.4.12
Underbridge space of the standard section of the gabion dike

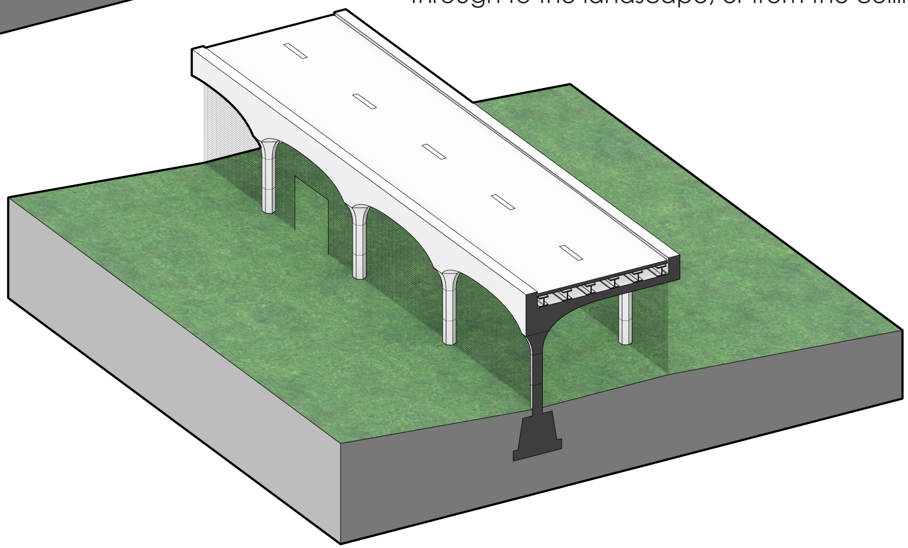


Figure 5.4.13
The standard section of the gabion dike

Figure 5.4.14
The Kralingseveer Light Festival

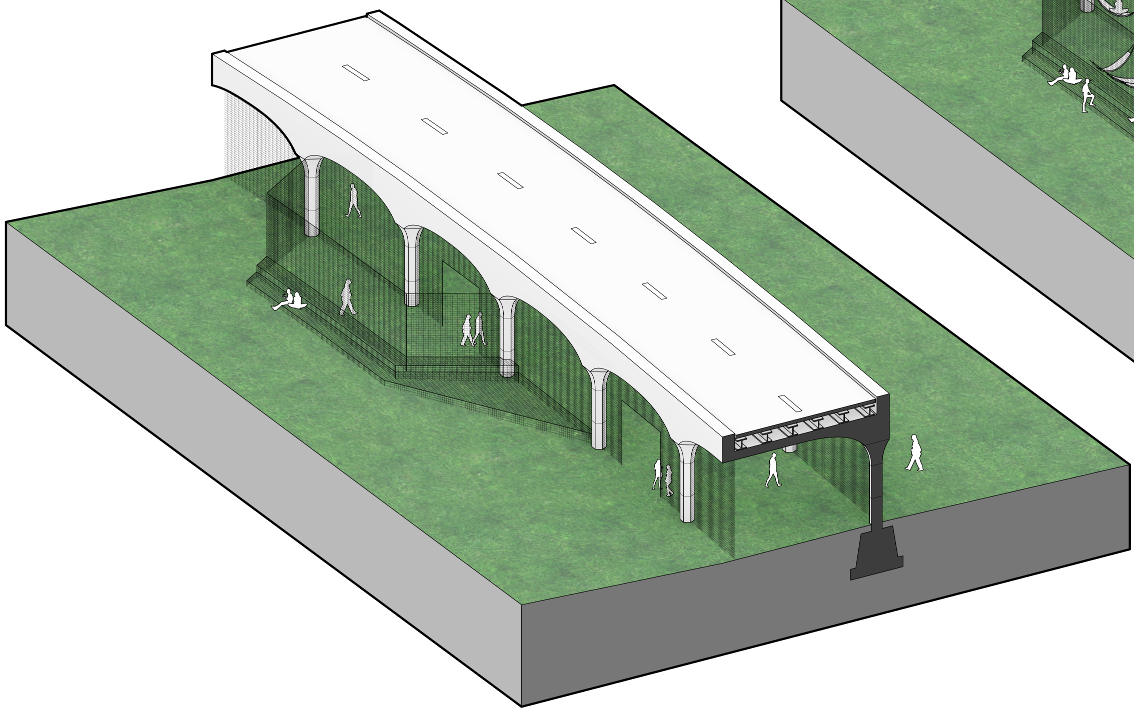


Figure 5.4.15
The activity section of the gabion dike

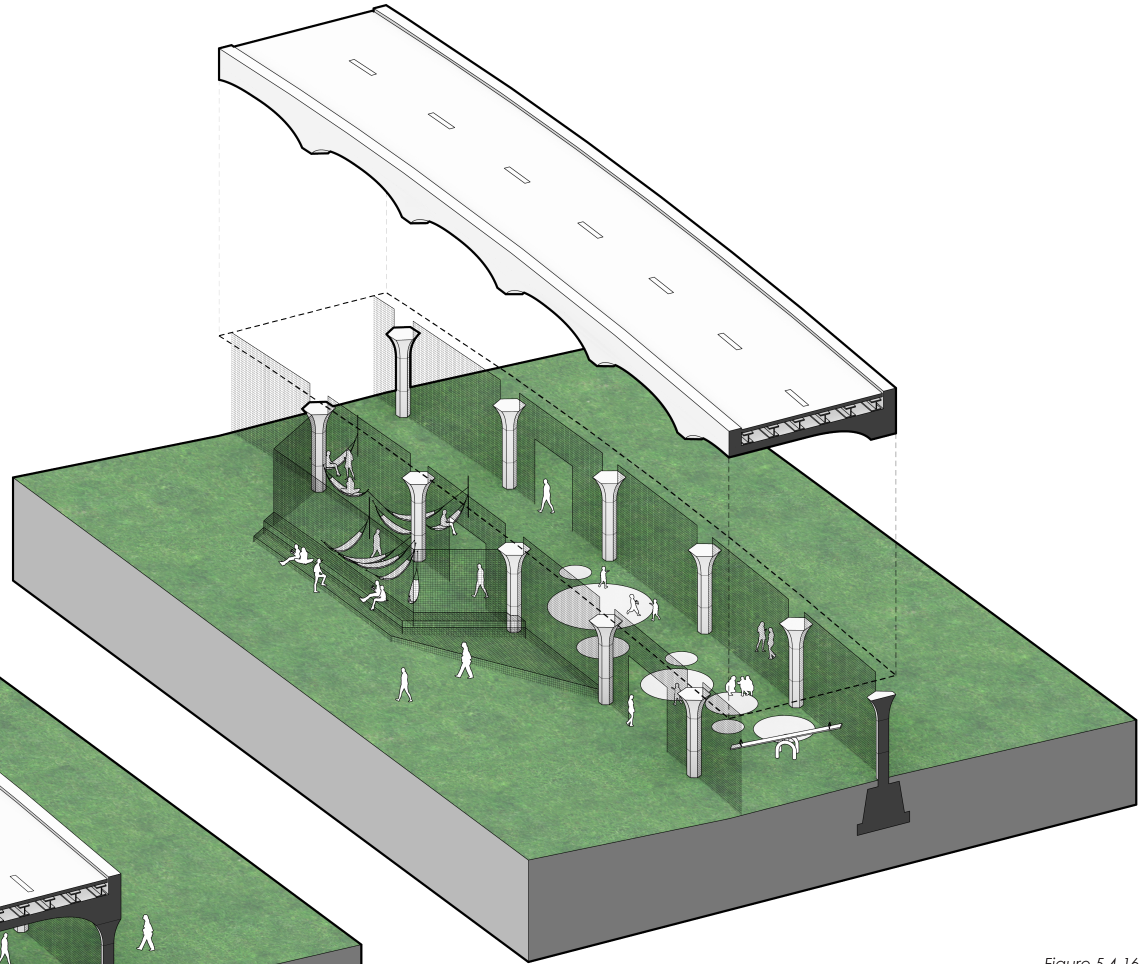


Figure 5.4.16
Underbridge space activity section of the gabion dike

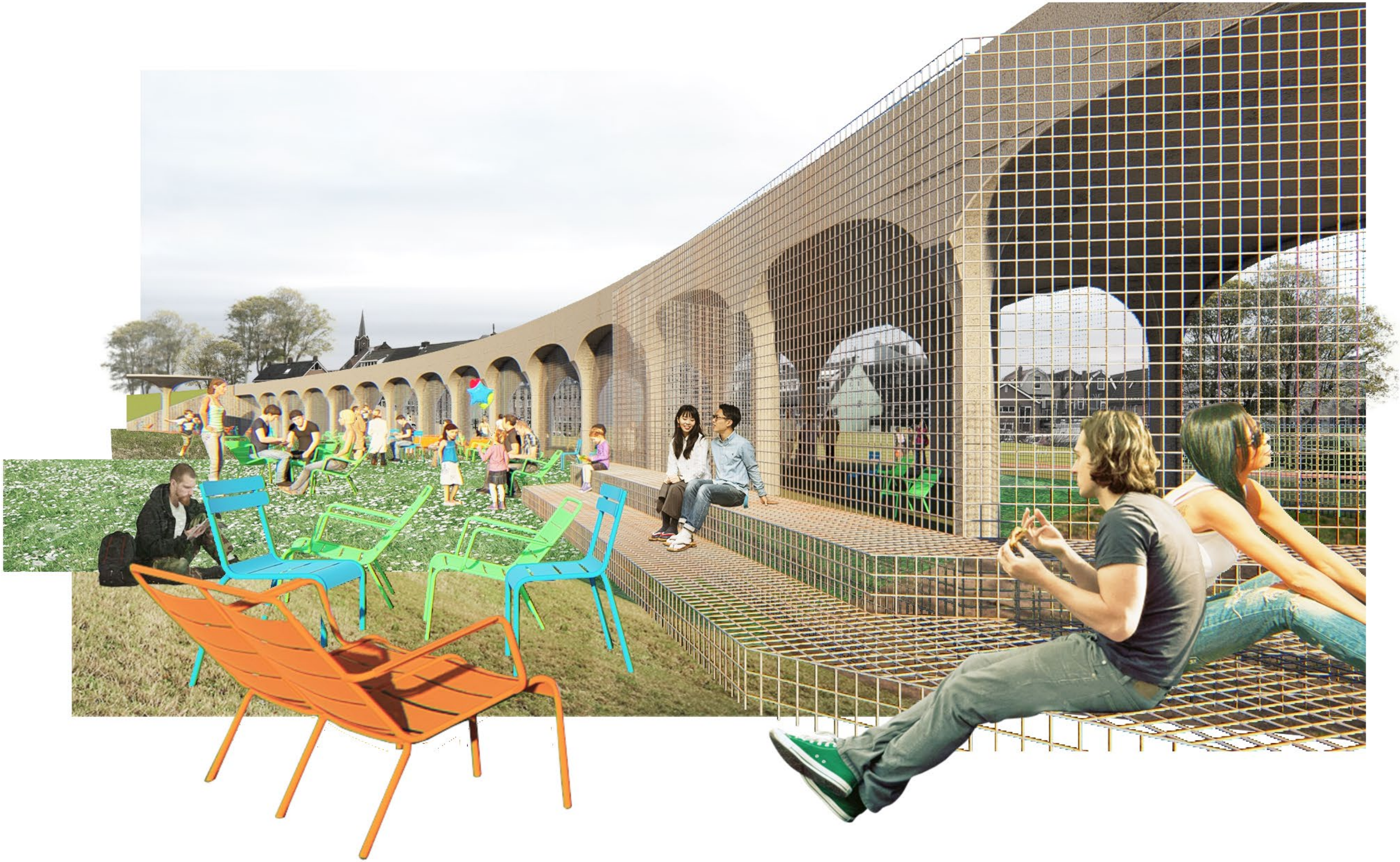


Figure 5.3.17 Outside the gabion dike

6 Discussion & conclusion

6.1 Discussion and limitation of the research

In this section, the research outcomes and methods for the each research question are discussed. The significance and contribution of the study, also the limitations and deficiency of the methods are involved in the discussion.

Site selection

The outcomes of site selection activity are the testbed and the prospect of seasonally adjustable flood defence structure in the Netherlands. The site selection was done manually, firstly by overlapping the urban heat map, the dike map and the river map on the national scale, then superimposing the urban topographies with the temperature gradients on the site scale. I basically checked Dutch cities one after another, following the path of the four main rivers: the Waal, the Rhine, the Maas and the Ijssel. In spite of the fact that it was very time-consuming, I could have neglected relatively small sites and possible sites along the river branches. Besides, the size of the floodplains and the terrain around the dikes were measured manually on Google Earth and the AHN website. The accuracy can not be ensured even though a lot of time was consumed.

For future study and practice, the selection activity can be done more efficiently in the geo-information system. Areas, such as floodplains, with certain characteristics can be selected and analysed based on information including surface temperature patterns, land-cover, NDVI (Normalized differences vegetation index) which are accessible from the Landsat satellite, together with the measured data of elevations, slopes and terrains (Jo, et al., 2001).

SRQ1

The first sub-research question was '**To what extent does the dike hamper the cool air exchange?**'. The Envi-met simulation and the literature study have been done to answer it.

According to the theoretical framework, the cool breeze needs to be studied contextually. Hereby, the ENVI-met simulations have been done to the abstracted models of the site to understand the cool air exchange spatially and temporally. In the ENVI-met simulation, the setting of a calm summer night (no regional-scale wind above 1.5m/s) was used. Still, 0 m/s of wind speed is the optimal simulation context to observe the cool breeze. However, ENVI-met can not work with the original setting of 0 m/s wind speed. So the lowest wind speed (0.1 m/s) coming from the summer dominant wind direction (230 South-west) was chosen. But even though the wind is very weak, it could still have a promotive influence on the ventilation that can not be neglected, because 230 south-west is almost parallel to the ventilation vector.

The original setting was getting less effective in the latter half of simulation. Compared with the results in the morning of 26th, the results in the evening and the night were more significant. 24-hour was chosen to be the simulation time span, which is theoretically the shortest timespan to simulate the situation. But the longer timespan is supposed to give a more convincing outcome because the microclimate effect could accumulate. If the simulation had been run for 48 hours or even 72 hours, the first sub-research question could be answered with higher accuracy.

SRQ2

The second sub-research question aimed to find **alternatives that optimize the flow of a cool breeze**. At the end of Design Loop 1, the eight concept models were categorized into three levels in terms of openness in the ventilation direction: completely open, mostly open and partly open.

In order to understand the relationship between ventilation efficiency and openness, another ENVI-met model with part of the dike remained, which represents the concept design those are 'mostly and partly open' was simulated as a supplementary study for the first round of simulation. By comparing the simulated temperature patterns between the three situations, the conclusion has been drawn. The concept design with more openness can provoke more efficient cool air exchange. In the end, the openness was assessed by visualizing their projections in the ventilation direction.

Nevertheless, this conclusion is rather general. Many other factors could influence the ventilation efficiency, such as the unique shape of the opening and the corner in the ventilation direction. Simulating the concept models respectively would be the most convincing but also time-consuming assessment approach. However, to do that, another microclimate simulation software with higher resolution is required. Due to the time span of a master thesis, no further stimulation was considered, and openness has been chosen as the only assessment criteria. It is believed that the assessment approach which currently is possible to misestimate the ventilation efficiency, is improvable by making more specific simulations.

SRQ3

In order to answer the third sub-research question, the three parallel site designs were made to explore **the potential of adjustable dike structures to create places providing social functions**.

Although the site design for the IJsseldijk is strongly contextual, it does not prevent those multifunctional ideas to be inspirational for other sites, in which the dike stands in between the floodplain and the urban area.

Furthermore, some of the programs, such as the hammock space, the semi-open cafe bar, the children playground and the marketplace, are also inspirational for other under-bridge spaces where flood defence and urban ventilation is not prioritized. In other words, the results for the third sub-research question can be relatively independent from the purpose of urban ventilation. The identified multifunctions are generically applicable for other sheltered spaces in or nearby the urban area, such as the place where bridge piers land on the floodplain and the space under urban or suburban viaducts.

MRQ

The main research question was looking for **new types of river dike provide flood defence, urban ventilation and social functions**.

This research through design process was a problem-oriented action, which started from solutions for better urban ventilation in the first design loop, followed by the second design loop to test the flood defence ability and the ultimate explorative site design to discover social functions. The optimal solutions were stepwise selected during the research through design process from the eight alternatives at the beginning to the three in the end. However, this prioritized selection procedure resulted in a consequence that the flood defence structures with high stability and multifunctionality but low score in ventilation had been excluded from the first design loop.

In practice, the flood defence function, rather than urban ventilation or other multifunctions has always been prioritized. Because different priorities could lead to different selection outcomes, it is worth to discuss here what if the flood defence function was prioritized in the research through design process. If the structural stability was considered as the prerequisite, the concept design of windows in the dike and the ‘drawbridge’ dike partition could have been given more attention. Conversely, the rotatable portadam might be excluded from the early stage.

6.2. Conclusion

SRQ1: To what extent does the dike trap the cool air?

This sub-research question was aiming to quantify and visualize the cool air exchange and the hampering effect on it. After understanding the fact that the cool breeze movement and its cooling effect are strongly contextual, the site-specific ENVI-met simulations indicated the dike starts to hamper the cool air around 18:00 pm and almost no cooling effect is received from the floodplain. Conversely, without the dike, the cool breeze is able to decrease the air temperature on the area of 180m into the neighbourhoods at the pedestrian level (1.8m). It is worth mentioning that the effect was measured in the first 24 hours of the simulation, and the cooling effect is likely to accumulate.

SRQ2: How can the adjustable dike structure optimize flow of a cool breeze?

The question was formed to generate innovative flood defence structures that can be adjusted according to the need of flood protection and urban heat problem mitigation. In order to allow and facilitate the movement of a cool breeze, the new dike structure needs to be openable especially on the ground level. According to the conclusion of SRQ1, a bigger opening in the dike is likely to provoke more efficient cool air exchange.

In conclusion, the inflatable dike partition, the modular & moveable floodwall and the gabion dike were tested to be the most promising design to optimize the cool breeze, and at the same time to ensure the stability of the flood defence structure. After that, the rotatable portadam performs parallel to the three optimal solutions in terms of ventilation, but it has a questionable flood defence ability. Moreover, the rotatable dike partition, the windows in the dike, the 'drawbridge' dike partition and the sliding floodgate achieve synergy with a cool breeze to different extents.

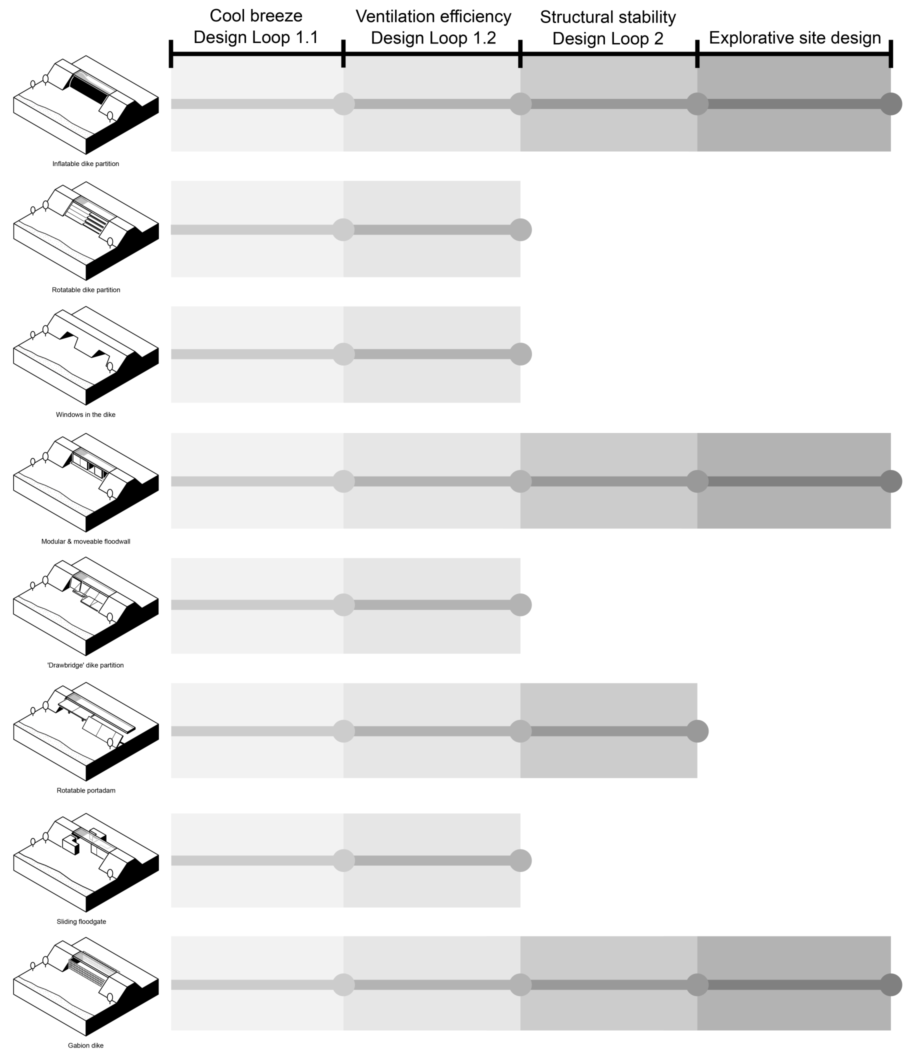


Figure 6.2.1 Overview of selection results

SRQ3: What is the potential of adjustable dike structures to create places providing social functions?

In addition to flood defence and urban ventilation, more social multifunctions were possible to be carried by the three optimal structures. Most of the year, flood defence and urban ventilation are not needed, that is when social functions take place. The rubber membrane, the concrete slabs and the gabion grid are respectively the crucial elements in the three optimal alternatives, which are both able to shape space.

Generally, the gabion dike performs the best in terms of multifunctionality. The semi-open space and the feature of hanging objects on the metal grid make it suitable for more social functions than the inflatable dike partition and the modular & moveable floodwall. From the perspective of multifunctional flood defence, most activities of the gabion dike are on the integration level of shared-use, which put a minimum risk on the original flood defence function. Another advantage is that only small interventions are required. To be specific, most of the social functions are achieved by hanging objects on the gabion, including hammocks, slacklines, swings, climbing holds, cloth hangers, lamps and curtains which is able to shape the rooms and switch them from semi-open to private. These objects are replaceable and relatively low-cost.

In the place created with the modular & moveable floodwalls, the modularity and flexibility of slabs enable the room of different sizes and shapes to serve the multiple activities including the exhibition hall, the theatre, the market, the concert, the cafe bar, the meeting room and climbing walls. These multifunctions are carried out on the level of functional integration which flood defence elements are also used as the structure for multifunctions. But it is different from the typical functional integration because the social functions and the flood defence never happen at the same time. Using the space and structure for multifunctions requires no extra constructional cost, while efforts are only needed in re-arranging the slabs. Moreover, those slabs are precast, which means low-prized, replaceable and easy to maintain.

The rubber bladder is a playful partition, which could not only create enclosure space but also hold media in the shaped space. Therefore, programs like a swimming pool, a skating field and a dance floor are feasible. And the activity space can be established and withdrawn by inflating and deflating the rubber membrane. Compared with the moveable floodwall and the gabion dike, the rubber dike is more expensive to construct and requires more inspection and maintenance. Moreover, every inflation for multifunction creates energy consumption.

To sum up, the gabion dike and the moveable floodwall create places for more neighbourhood-oriented functions, especially for the ageing community like Kralingseveer. And nearly no extra construction is required for the multifunctions. Conversely, the inflatable dike partition provides more tourist attractive and eye-catching functions and may have the educational value of urban climate.

MRQ: How can new types of river dike provide flood defence, urban ventilation and social functions?

The main research question was aiming to generate new types of the river dike to mitigate urban heat problems, and at the same time create social space. The inflatable dike partition, the rotatable dike partition, the windows in the dike, the modular & moveable floodwall, the 'drawbridge' dike partition, the rotatable portadam, the sliding floodgate and the gabion dike were proposed, based on the understanding of cool air exchange between the floodplain and the urban area, and identified to have a synergistic effect to facilitate urban ventilation.

Amongst the eight adjustable flood defence structures, the design of gabion dike is most suitable for the testbed, because it achieves the equal ventilation efficiency with the inflatable dike partition and the modular & moveable floodwall but requires simpler interventions. In addition, it provides more sustainable and neighbourhood-oriented multifunctions. On the other hand, the modular & moveable floodwall is the most generically applicable structure. Besides, the inflatable dike partition is the most promising solution for the future, because it has been tested in practice to be very flexible and robust in terms of flood protection. It requires more construction at the beginning but is more user-friendly in the afterwards operation.

6.3 Relevance

Scientific relevance

Former climatic researchers have never focused on the microclimate effect of river dikes in Dutch context. This thesis quantitatively studied the river dike's hampering effect on the cool air exchange and demonstrated the cooling potential of a thermal-driven breeze between floodplains and urban heat areas. Therefore, it fills in the knowledge gap in urban microclimate.

So far, no scientific research has discussed dike alternatives from the perspective of urban climate, let alone for mitigating urban heat problems. In order to optimize the cool breeze, inspirations were found from existing hydraulic projects, books about multifunctional flood defence, temporary flood defence measures and other objects in daily life to design adjustable dike structures that are synergistic with urban heat mitigation. Therefore, this thesis fills in a knowledge gap in flood defence design. Moreover, this thesis lists a series of potential sites in the Netherlands for further research and practice.

Next to that, this thesis explored a new direction of making multifunctional flood defence, which integrates flood defence, urban ventilation and social functions on the temporal dimension, while previous research mainly worked on multifunctionality on the spatial dimension.

Societal relevance

The academic environment is more tolerant for innovations, so the pioneering research through design process could be conduct. This process explored the possibility of integrating flood defence, urban ventilation and social functions in one structure which designers and hydraulic engineers could not attempt in the practical context due to safety and economic reasons. This thesis provides the prototypes of adjustable dikes and the reference of multifunctional flood defence for practitioners.

The cool breeze between floodplains and urban areas will become a more valuable ventilation resource during climate change and urbanization. The new multifunctional dikes were designed to optimize the effect of cool breeze, which help to improve the quality of outdoor space. Next to that, the shared social functions invite urban residents to get close to the water facilities and from there they gain the awareness about urban heat mitigation and climate change adaptation.

REFERENCES

Anvarifar, F., Zevenbergen, C., Thissen, W., & Islam, T. (2016). Understanding flexibility for multifunctional flood defences: a conceptual framework. Journal of Water and Climate Change, 7(3), 467-484.

Albers, R. A. W., Bosch, P. R., Blocken, B. J. E., Dobbelsteen, A. A. J. F., Hove, van, L. W. A., Spit, T. J. M., ... Rovers, V. (2015). Overview of challenges and achievements in the climate adaptation of cities and in the Climate Proof Cities program. Building and Environment, 83, 1-10. https://doi.org/10.1016/j.buildenv.2014.09.006

Baruh, B. G. (2000). U.S. Patent No. 6,164,870. Washington, DC: U.S. Patent and Trademark Office.

Bedient, P. B., Berchum, E., Blackburn, J. B., De Boer, R., Van Brakel, S., Van Breukelen, M., ... & Dupuits, G. (2015). Delft Delta Design: The Houston Galveston Bay Region, Texas, USA. Delft University Publishers, TU Delft Library.

Buyantuyev, A., & Wu, J. (2010). Urban heat islands and landscape heterogeneity: linking spatiotemporal variations in surface temperatures to land-cover and socioeconomic patterns. Landscape ecology, 25(1), 17-33.

Biggar, K. W., & Masala, S. (1998). Alternatives to sandbags for temporary flood protection. Alberta Transportation and Utilities, Disaster Services Branch and Emergency Preparedness Canada.

Brown, R. D. (2010). Design with microclimate: the secret to comfortable outdoor space. Island Press.

Bisker, J., Chester, A., & Eisenberg, T. (2015). Rebuild by design. New York, NY, available at: www. rebuildbydesign. org/data/files/500. pdf (accessed 27 July 2019).

Barden, L. (2016). THE LA RIVER COMES OF AGE. Retrieved 10 March 2020, from https://artillerymag.com/la-river-comes-age/

Choi, S. Y., Lee, Y. H., Cho, C., & Kim, K. R. (2015). Analysis of local wind induced by surface heterogeneity and sloping terrain near Nakdong river. Asia-Pacific Journal of Atmospheric Sciences, 51(3), 249-257.

Clements, C. B., Whiteman, C. D., & Horel, J. D. (2003). Cold-air-pool structure and evolution in a mountain basin: Peter Sinks, Utah. Journal of Applied Meteorology, 42(6), 752-768

Climate Impact Atlas - Klimaateffectatlas. (2020). Retrieved 5 March 2020, from http://www.klimaateffectatlas.nl/en/

Douben, N., Silva, W., Klopstra, D., & Kok, M. (2007). Decision support and river management strategies for the Rhine in the Netherlands. ARABIAN JOURNAL FOR SCIENCE AND ENGINEERING, 32(1C), 17.

Dakpark Rotterdam - Buro Sant en Co. (2020). Retrieved 28 February 2020, from https://www.santenco.nl/nl/portfolio_page/dakpark/

Erell, E., Dennis., N., Williamson, T., & Pearlmutter, D. (2011). Urban Microclimate: Designing the Spaces Between Buildings (Designing the Spaces Between Buildings)

Eijgenraam, C. J. (2006). Optimal safety standards for dike-ring areas. Discussion paper nr. 62, ISBN 90-5833-267-5.

Flood protection by an inflatable rubber dam: Balgstuw Ramspol. (2020). Retrieved 28 February 2020, from https://www.government.nl/documents/videos/2014/01/09/flood-protection-by-an-inflatable-rubber-dam

Geschiedenis – Laankerk.nl. (2017). Retrieved 5 March 2020, from https://www.laankerk.nl/?page_id=8751

Ghiaus, C., Allard, F., Santamouris, M., Georgakis, C., & Nicol, F. (2006). Urban environment influence on natural ventilation potential. Building and environment, 41(4), 395-406.

Hambly, E. C. (1991). Bridge deck behaviour. CRC Press.

Huttner, S. (2012). Further development and application of the 3D microclimate simulation ENVI-met. Mainz: Johannes Gutenberg-Universitat in Mainz, 147.

Heusinkveld, B. G., Steeneveld, G. V., Van Hove, L. W. A., Jacobs, C. M. J., & Holtslag, A. A. M. (2014). Spatial variability of the Rotterdam urban heat island as influenced by urban land use. Journal of Geophysical Research: Atmospheres, 119(2), 677-692.

Hidalgo, J., Masson, V., & Pigeon, G. (2008). Urban-breeze circulation during the CAPITOUL experiment: numerical simulations. Meteorology and Atmospheric Physics, 102(3-4), 243.

Jackson III, J. G. (1987). U.S. Patent No. 4,692,060. Washington, DC: U.S. Patent and Trademark Office.
Jo, M. H., Lee, K. J., Jun, B. W., Kwon, B. K., & Jo, Y. W. (2001, November). The spatial topographic analysis of urban surface temperature using remotely sensed data and GIS. In 22nd Asean Conference on Remote Sensing.
Klok, L., Zwart, S., Verhagen, H., & Mauri, E. (2012). The surface heat island of Rotterdam and its relationship with urban surface characteristics. Resources, Conservation and Recycling, 64, 23-29
Krautheim, M., Pasel, R., Pfeiffer, S., & Schultz-Granberg, J. (2014). CITY AND WIND-Climate as an architectural Instrument.
Kok, M. (2017). Societal need for multifunctional flood defenses: Introduction. Integral Design of Multifunctional Flood Defenses.
Kothuis, B. L. M., & Kok, M. (2017). Integral Design of Multifunctional Flood Defenses. Delft University Publisher (Vol. 166, p. 174). Delft University Publishers. Retrieved from https://www.hkv.nl/upload/publication/Multifunctional_Flood_Defenses_LowRes_MK_WEBSITE.pdf.
KNMI - Daggegevens van het weer in Nederland. (2020). Retrieved 10 March 2020, from https://www.knmi.nl/nederland-nu/klimatologie/daggegevens
Klijn, F., Asselman, N., & Wagenaar, D. (2018). Room for Rivers: Risk Reduction by Enhancing the Flood Conveyance Capacity of The Netherlands' Large Rivers. Geosciences, 8(6), 224.
Lenzholzer, S. (2015). Weather in the City - How Design Shapes the Urban Climate. Nai 010 Uitgevers/Publishers.
Lenzholzer, S., & Brown, R. D. (2013). Climate-responsive landscape architecture design education. Journal of Cleaner Production, 61, 89-99
Learning & Support - ENVI-met. (2020). Retrieved 3 March 2020, from https://www.envi-met.com/learning-support/
Leo, L. S., Fernando, H. J. S., & Di Sabatino, S. (2015). Near-surface flow in complex terrain with coastal and urban influence. Environmental Fluid Mechanics, 15(2), 349-372.
Liu, S. Y., & Shen, J. H. (2010). Urban ventilation channel planning method based on local circulation: a case study of Stuttgart, Germany. Journal of Zhejiang University (Engineering Science), 10, 1985-1991.
Meyer, H., & Hermans, W. (2009). Adaptive strategies and the Rotterdam floodplain. Delft, The Netherlands: TU-Delft.
NYC: The BIG U | Rebuild By Design. (2014). Retrieved 9 March 2020, from http://www.rebuildbydesign.org/our-work/all-proposals/winning-projects/big-u
Oke, T. R., Mills, G., Christen, A., & Voogt, J. A. (2017). Urban climates. Cambridge University Press.
Pleijster, E. J., van der Veeken, C., Jongerius, R., & Luiten, E. A. J. (2014). Dutch dikes. nai010 publishers.
Raaphorst, K. M. C. (2017). 'Deconstructing'the Rotterdam roof park: Multiplicity of design representations. In Integral design of multifunctional flood defenses (pp. 174-177). Delft University Publishers TU Delft Library.
Ruimte voor de Rivier. (2019). Retrieved 10 March 2020, from https://www.ruimtevoorderivier.nl/
Reeve, D., & Badr, A. (2003, December). Performance of sandbags for domestic flood defence. In Proceedings of the Institution of Civil Engineers-Water and Maritime Engineering(Vol. 156, No. 4, pp. 341-349). Thomas Telford Ltd.
Scherer, D., Fehrenbach, U., Beha, H. D., & Parlow, E. (1999). Improved concepts and methods in analysis and evaluation of the urban climate for optimizing urban planning processes. Atmospheric Environment, 33(24-25), 4185-4193.
Serafin, S., & Zardi, D. (2010). Daytime heat transfer processes related to slope flows and turbulent convection in an idealized mountain valley. Journal of the Atmospheric Sciences, 67(11), 3739-3756
Sugawara, H., Shimizu, S., Takahashi, H., Hagiwara, S., Narita, K. I., Mikami, T., & Hirano, T. (2016). Thermal influence of a large green space on a hot urban environment. Journal of environmental quality, 45(1), 125-133.
Sugawara, H., Narita, K. I., & Kim, M. S. (2009, June). Cooling effect by urban river. In The 7th International Conference on Urban Climate (Vol. 29).
Thomson, I. R. (2011). U.S. Patent No. 7,922,426. Washington, DC: U.S. Patent and Trademark Office.
Unger, J., Sümeghy, Z., Gulyás, Á., Bottyán, Z., & Mucsi, L. (2001). Land-use and meteorological aspects of the urban heat island. Meteorological Applications, 8(2), 189-194.
Van der Hoeven, F., & Wandl, A. (2018). Hotterdam: Mapping the social, morphological, and land-use dimensions of the Rotterdam urban heat island. Urbani izziv, 29(1), 58-72.

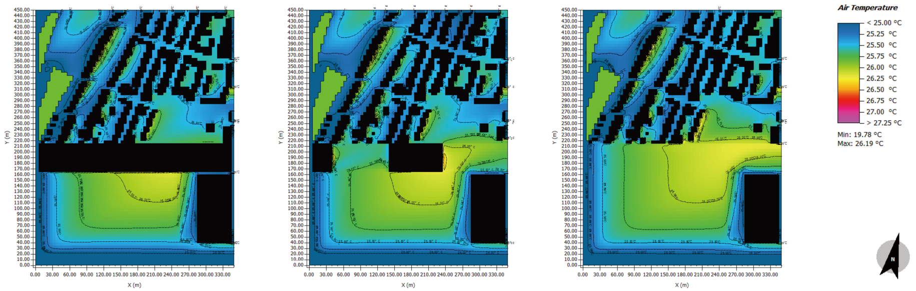
van Veelen, P., Voorendt, M., & van der Zwet, C. (2015). Design challenges of multifunctional flood defences. A comparative approach to assess spatial and structural integration. Research in Urbanism Series, 3, 275-292.
Voorendt, M. (2017). Structural evaluation of multifunctional flood defenses. Integral Design of Multifunctional Flood Defenses.
Voorendt, M. Z. (2017). Design principles of multifunctional flood defences.
Vrijling, J. K. (2017). Multifunctional flood defenses: Technical design problem or policy challenge?. Integral Design of Multifunctional Flood Defenses.
Van Hove, L. W. A., Steeneveld, G. J., Jacobs, C. M. J., Heusinkveld, B. G., Elbers, J. A., Moors, E. J., & Holtslag, A. A. M. (2011). Exploring the urban heat island intensity of Dutch cities: assessment based on a literature review, recent meteorological observation and datasets provide by hobby meteorologists (No. 2170). Alterra.
Ven, G. (2004). Man-made lowlands. Utrecht: Uitgeverij Matrijs.
Whyte, W. H. (1980). The social life of small urban spaces.
Yu, C., & Hien, W. N. (2006). Thermal benefits of city parks. Energy and buildings, 38(2), 105-120.
Yuan, C. (2018). Urban Wind Environment: Integrated Climate-Sensitive Planning and Design. Springer.
Zhang, X. Q., Tam, P. W., & Zheng, W. (2002). Construction, operation, and maintenance of rubber dams. Canadian Journal of Civil Engineering, 29(3), 409-420.
Zhong, S., Leone, J. M., & Takle, E. S. (1991). Interaction of the sea breeze with a river breeze in an area of complex coastal heating. Boundary-layer meteorology, 56(1-2), 101-139.

FIGURES

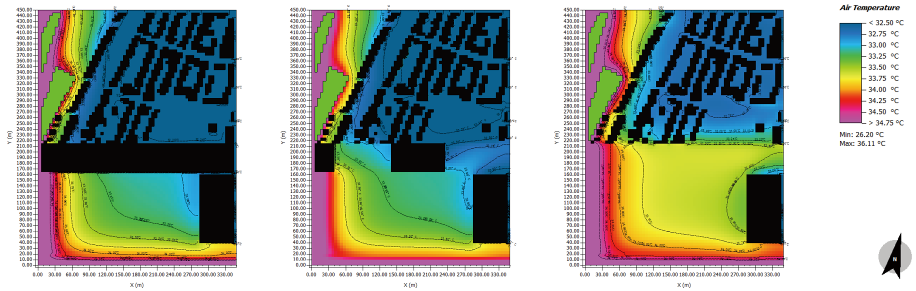
Figure 3.4.2	Kralingseveer in 1918 (Geschiedenis – Laankerk.nl. (2017). Retrieved 5 March 2020, from https://www.laankerk.nl/?page_id=8751)
Figure 3.4.5	Tri-border-area between Rotterdam Municipality, Capelle aan den IJssel Municipality and Krimpen aan den IJssel Municipality (Zuid-Holland (Province, Netherlands) - Population Statistics, Charts, Map and Location. (2020). Retrieved 8 March 2020, from https://www.citypopulation.de/en/netherlands/admin/NL33__zuid_holland/)
Figure 3.4.6	Demographic information of Capelle aan den IJssel Municipality (Capelle aan den IJssel (Municipality, Zuid-Holland, Netherlands) - Population Statistics, Charts, Map and Location. (2020). Retrieved 8 March 2020, from https://www.citypopulation.de/en/netherlands/admin/zuid_holland/0502__capelle_aan_den_IJssel/)
Figure 3.4.7	Demography information of Rotterdam municipality (Rotterdam (Municipality, Zuid-Holland, Netherlands) - Population Statistics, Charts, Map and Location. (2020). Retrieved 8 March 2020, from https://www.citypopulation.de/en/netherlands/admin/zuid_holland/0599__rotterdam/)
Figure 4.1.8	The Laankerk (Geschiedenis – Laankerk.nl. (2017). Retrieved 5 March 2020, from https://www.laankerk.nl/?page_id=8751)
Figure 4.1.9	The heatwave records from 1911 to 2019 (KNMI - Hittegolven. (2020). Retrieved 1 April 2020, from https://www.knmi.nl/nederland-nu/klimatologie/lijsten/hittegolven)
Figure 4.2.3	The operational process of Ramspol Inflatable Dam when deflated (Flood protection by an inflatable rubber dam: Balgstuw Ramspol. (2020). Retrieved 28 February 2020, from https://www.government.nl/documents/videos/2014/01/09/flood-protection-by-an-inflatable-rubber-dam)
Figure 4.2.4	The operational process of Ramspol Inflatable Dam when inflated (Flood protection by an inflatable rubber dam: Balgstuw Ramspol. (2020). Retrieved 28 February 2020, from https://www.government.nl/documents/videos/2014/01/09/flood-protection-by-an-inflatable-rubber-dam)
Figure 4.2.5	The rubber dam of the Tempe Town Lake in Tempe, Arizona (File:Tempe Town Lake - West Dams - 2009-09-04.JPG - Wikimedia Commons. (2009). Retrieved 2 March 2020, from https://commons.wikimedia.org/wiki/File:Tempe_Town_Lake_-_West_Dams_-_2009-09-04.JPG)
Figure 4.2.13	The bulkheads close the coupure on the Boterdijk (Hendriks, A. (2019). 'Wij gebruiken geen paardenmest!'. Retrieved 27 March 2020, from https:/www.zevenaarpost.nl/nieuws/algemeen/830798/-wij-gebruiken-geen-paardenmest-)
Figure 4.2.17	The bulkheads storage (Henkv, D. (2014). Papsluis Schotbalken.JPG. Retrieved 27 March 2020, from https://nl.wikipedia.org/wiki/Bestand:Papsluis_Schotbalken.JPG)
Figure 4.2.18	The gate in flood defence wall near to West Bay, Dorset, Great Britain (Mykura, N. (2014). Access Gate in Flood Defence Wall (C) Nigel Mykura. Retrieved 2 March 2020, from https://www.geograph.org.uk/photo/3853858)
Figure 4.2.19	The floodwall at Zruč nad Sázavou, Czech Republic (File:Zruč nad Sázavou, Ostrovský potok, u Vlašimské ulice.jpg - Wikimedia Commons. (2013). Retrieved 13 April 2020, from https://commons.wikimedia.org/wiki/File:Zru%C4%8D_nad_S%C3%A1zavou,_Ostrovsk%C3%BD_potok,_u_Vla%C5%A1imsk%C3%A9_ulice.jpg)
Figure 4.2.22	The drawbridge at Threave Castle (Attacking and defending castles. (2020). Retrieved 1 April 2020, from https://www.bbc.co.uk/bitesize/topics/z74jpv4/articles/zhrb6v4)
Figure 4.2.23	The rotatable portadam (Based on Bedient, P. B., Berchum, E., Blackburn, J. B., De Boer, R., Van Brakel, S., Van Breukelen, M., ... & Dupuits, G. (2015). Delft Delta Design: The Houston Galveston Bay Region, Texas, USA. Delft University Publishers, TU Delft Library.)
Figure 4.2.25	The temporary flood defence element in the project of Bolivar Peninsula (Bedient, P. B., Berchum, E., Blackburn, J. B., De Boer, R., Van Brakel, S., Van Breukelen, M., ... & Dupuits, G. (2015). Delft Delta Design: The Houston Galveston Bay Region, Texas, USA. Delft University Publishers, TU Delft Library.)
Figure 4.2.26	The working procedure of Portadam (Portadam. Retrieved 28 March 2020, from http://www.csigeo.com/Portadam.html)
Figure 4.3.2	The rubber dam on the Los Angeles River (Barden, L. (2016). THE LA RIVER COMES OF AGE. Retrieved 10 March 2020, from https://artillerymag.com/la-river-comes-age/)
Figure 4.3.5	Application of metal grid panel as pavement (Pressed grating - OMAF - Grigliati Pressati. (2018). Retrieved 30 March 2020, from https://omaf.it/pressed-grating/?lang=en)
Figure 4.3.8	The 'stop-log dike' (Kent, C. (2020). Dorpsraad Arcen voelt zich niet gehoord. Retrieved 1 April 2020, from https://maasduinencentraal.nl/dorpsraad-arcen-voelt-zich-niet-gehoord/)

Figure 4.3.9	Samples of the concrete slab with metal edge (Stelcon bedrijfsterrein producten - Stelcon. (2020). Retrieved 7 March 2020, from https://www.stelcon.nl/producten/bedrijfsterrein/)
Figure 4.3.10	Samples of the concrete slab (Koop voordelig uw betonplaten bij Totaal Bestrating!. (2020). Retrieved 7 March 2020, from https://www.totaalbestrating.nl/product/industrie-betonplaat-200x200x14cm-glad/)
Figure 4.3.18	Hesco concertainer installation: Stretching the cage (Biggar, K. W., & Masala, S. (1998). Alternatives to sandbags for temporary flood protection. Alberta Transportation and Utilities, Disaster Services Branch and Emergency Preparedness Canada.)

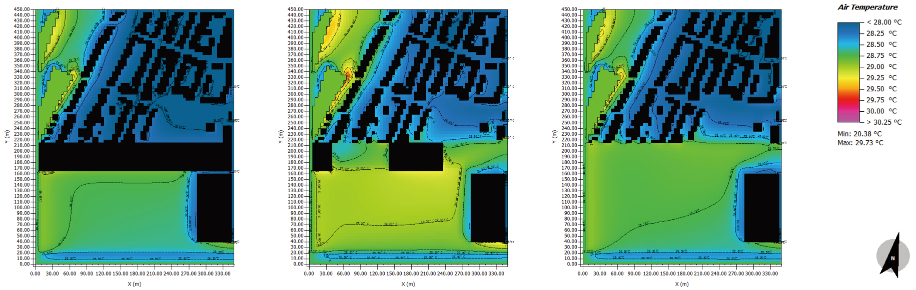
APPENDIX I
ENVI-met outcomes



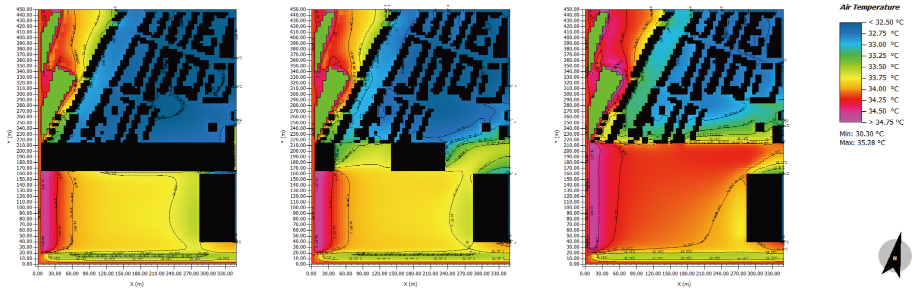
At 8:00, 26th, 2018



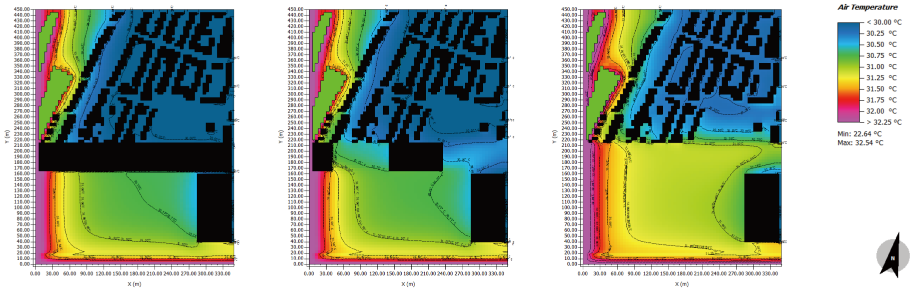
At 14:00, 26th, 2018



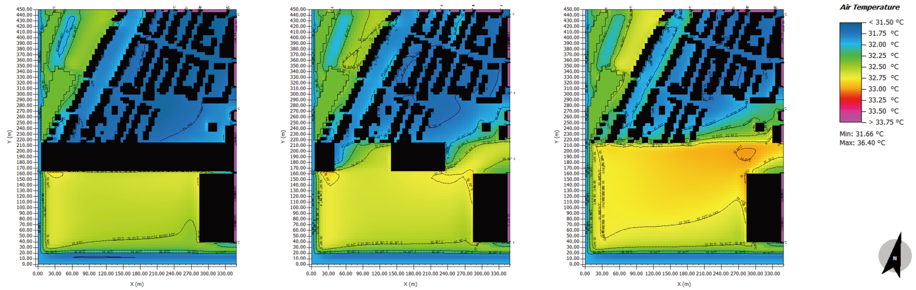
At 10:00, 26th, 2018



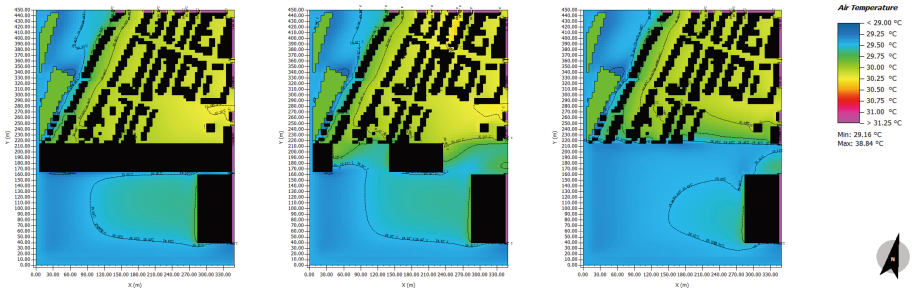
At 16:00, 26th, 2018



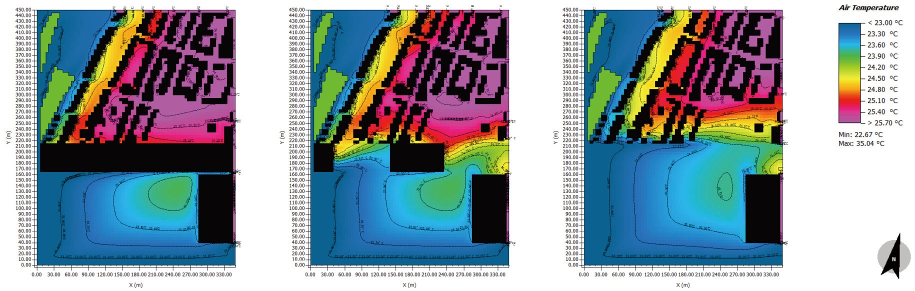
At 12:00, 26th, 2018



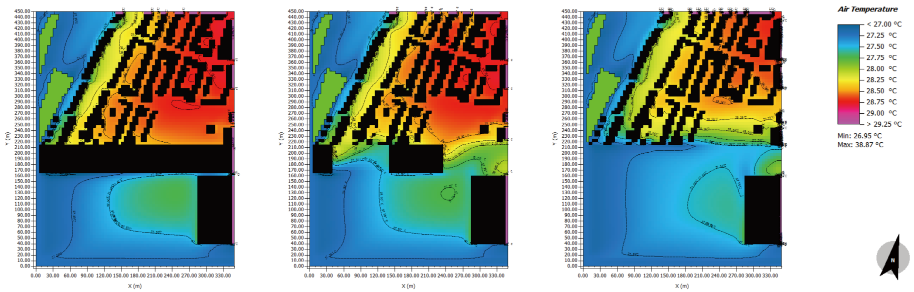
At 18:00, 26th, 2018



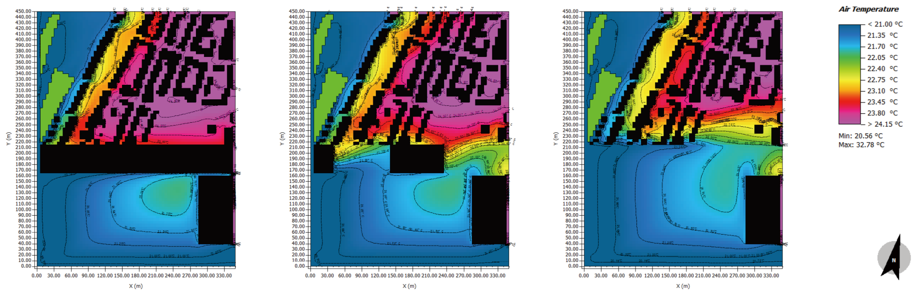
At 20:00, 26th, 2018



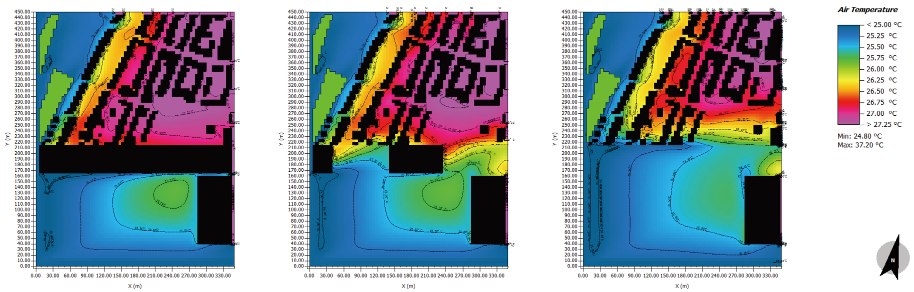
At 2:00, 27th, 2018



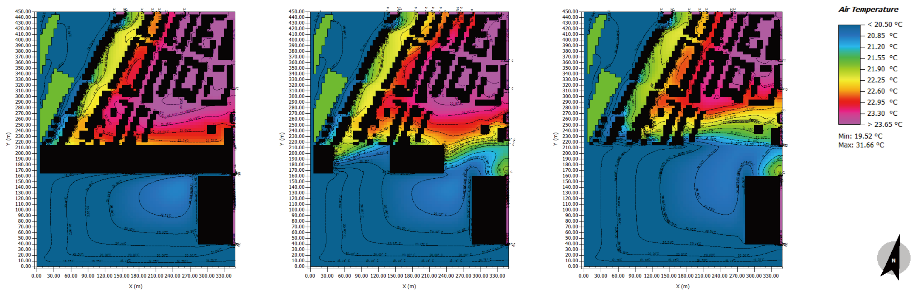
At 22:00, 26th, 2018



At 4:00, 27th, 2018



At 24:00, 26th, 2018

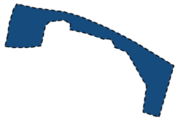


At 5:00, 27th, 2018

APPENDIX II
Potential sites in the Netherlands

Site name: Kralingseveer
Close to city: Rotterdam alexander
Beside river: Hollandse ijssel, Nieuwe maas
Area: 8.1 Ha
Current status: Heath, shipyard

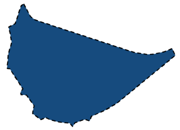
Site name: Nijverheidstraat
Close to city: Rotterdam alexander
Beside river: Hollandse ijssel
Area: 2.8 Ha
Current status: Shipyard



Site name: Uiterdijk
Close to city: Schiedam
Beside river: Nieuwe maas
Area: 16.4 Ha
Current status: Park

Site name: Havendijk
Close to city: Schiedam
Beside river: Nieuwe maas
Area: 7.4 Ha
Current status: Park

Site name: Dalemsedijk
Close to city: Gorinchem
Beside river: Waal
Area: 80.5 Ha
Current status: Heath, swamp



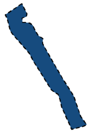
Site name: Schaardijk
Close to city: Kralingen-oost
Beside river: Nieuwe maas
Area: 38.2 Ha
Current status: Heath, wood

Site name: Bergse maas
Close to city: Raamsdonksveer
Beside river: Bergse maas
Area: 34.4 Ha
Current status: Heath, wood, beach

Site name: Empelsedijk/Maasboulevard
Close to city: Den bosch
Beside river: Meuse
Area: 117.3 Ha
Current status: Arable fields, beach

Site name: Zornerdijk
Close to city: Waaldijk
Beside river: Bergse maas
Area: 43 Ha
Current status: Arable fields

Site name: Geldersedijk
Close to city: Hattem
Beside river: Ijssel
Area: 31.1 Ha
Current status: Swamp, arable fields

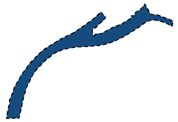


Site name: Holtenbroekerdijk
Close to city: Zwolle
Beside river: Ijssel
Area: 3.5 Ha
Current status: Heath

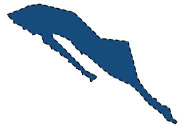
Site name: Veenoordkolk
Close to city: Deventer
Beside river: Ijssel
Area: 17.5 Ha
Current status: Heath, pond

Site name: Bronsbergen
Close to city: De strven
Beside river: Ijssel
Area: 49.9 Ha
Current status: Heath, arable fields

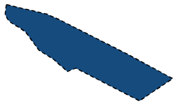
Site name: Letlandsestraat
Close to city: Zutphen
Beside river: Ijssel
Area: 17.2 Ha
Current status: Heath



Site name: Broekhuizerwater
Close to city: Doesburg
Beside river: Ijssel
Area: 7.8 Ha
Current status: Heath

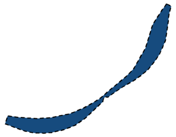


Site name: Waaldijk
Close to city: Nijmegen
Beside river: Waal
Area: 103.2 Ha
Current status: Arable fields, pond, beach



Site name: Broekhuizerwater
Close to city: Doesburg
Beside river: Oude ijssel
Area: 23 Ha
Current status: Heath

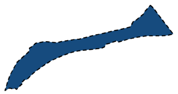
Site name: Bingerdensdijk
Close to city: Giesbeek
Beside river: Ijssel
Area: 22.9 Ha
Current status: Heath, beach



Site name: Rijksweg
Close to city: Rheden
Beside river: Ijssel
Area: 12.8 Ha
Current status: Heath

Site name: Broekdijk
Close to city: Velp
Beside river: Ijssel
Area: 87.3 Ha
Current status: Arable fields

Site name: Ijsseldijk
Close to city: Westervoort
Beside river: Ijssel
Area: 58.2 Ha
Current status: Arable fields, heath

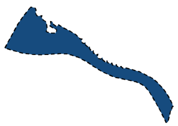


Site name: Schaapdijk
Close to city: Arnhem
Beside river: Ijssel
Area: 29 Ha
Current status: Arable fields

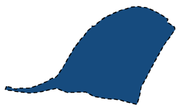
Site name: Pleijweg
Close to city: Arnhem
Beside river: Ijssel, Rhine
Area: 50 Ha
Current status: Arable fields

Site name: Echteldsedijk
Close to city: Tiel
Beside river: Waal
Area: 31.4 Ha
Current status: Heath, pond

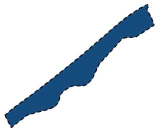
Site name: Stadsdam
Close to city: Zilverkamp
Beside river: Rhine
Area: 209 Ha
Current status: Arable fields



Site name: Malburgse Bandijk
Close to city: Malburgen
Beside river: Rhine
Area: 64 Ha
Current status: Arable fields

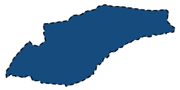


Site name: Drielsedijk
Close to city: Arnhem
Beside river: Rhine
Area: 223.5 Ha
Current status: Park, pond



Site name: Broekdijk
Close to city: Velp
Beside river: Rhine
Area: Ha
Current status: Arable fields

Site name: Ijsseldijk
Close to city: Westervoort
Beside river: Rhine
Area: 21.6 Ha
Current status: Arable fields, heath

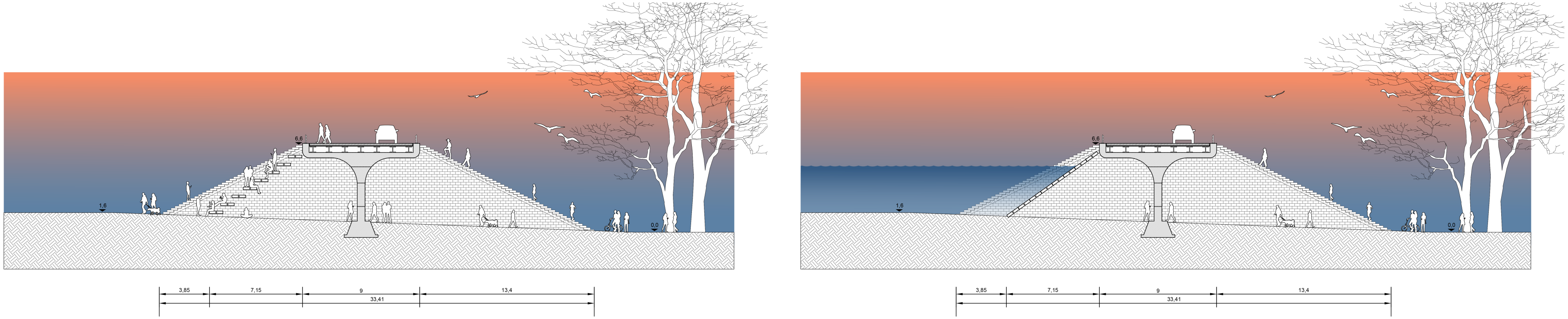


Site name: Grebbedijk
Close to city: Wageningen
Beside river: Rhine
Area: 161 Ha
Current status: Heath

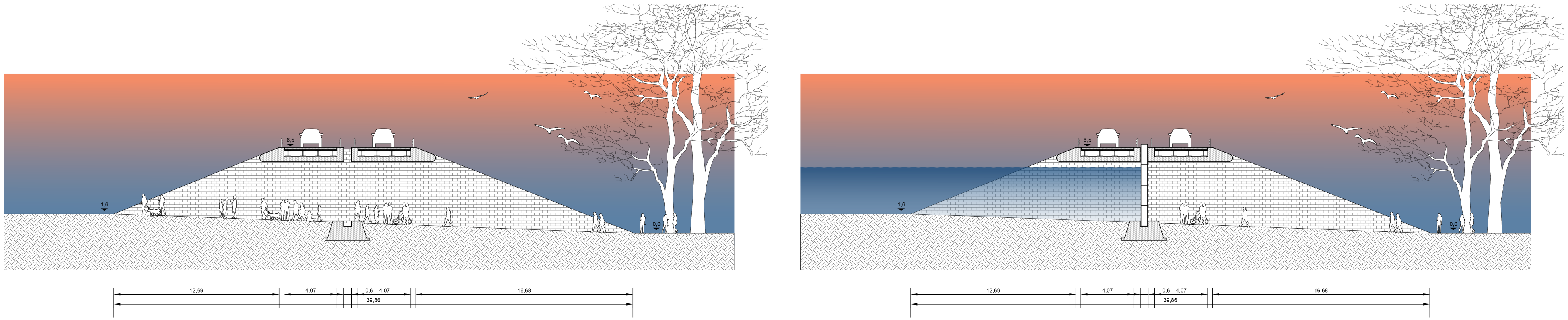
Site name: Ringdijk/Lekdijk
Close to city: Vianen
Beside river: De lek
Area: 90.3 Ha
Current status: Arable fields

Site name: Ophemertsedijk
Close to city: Tiel
Beside river: Waal
Area: 9.8 Ha
Current status: Heath

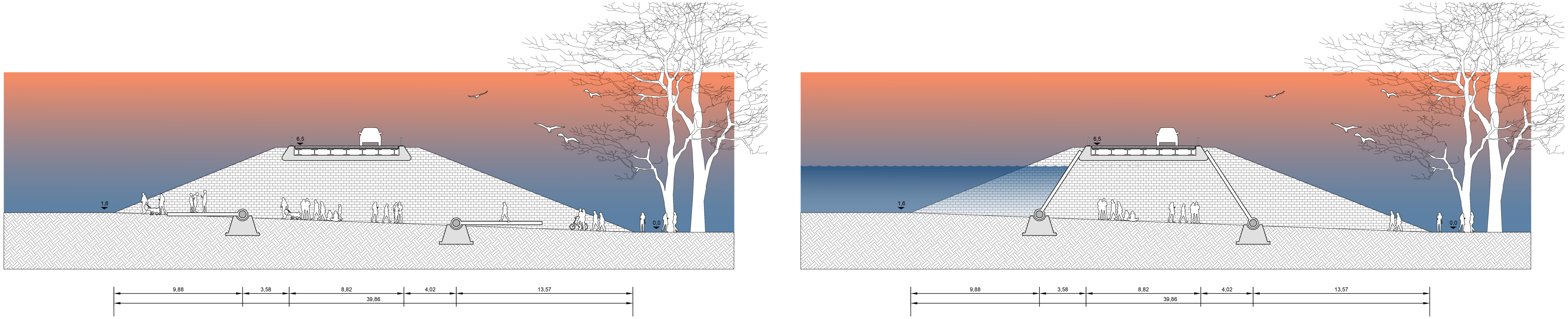
APPENDIX III
Technical sections



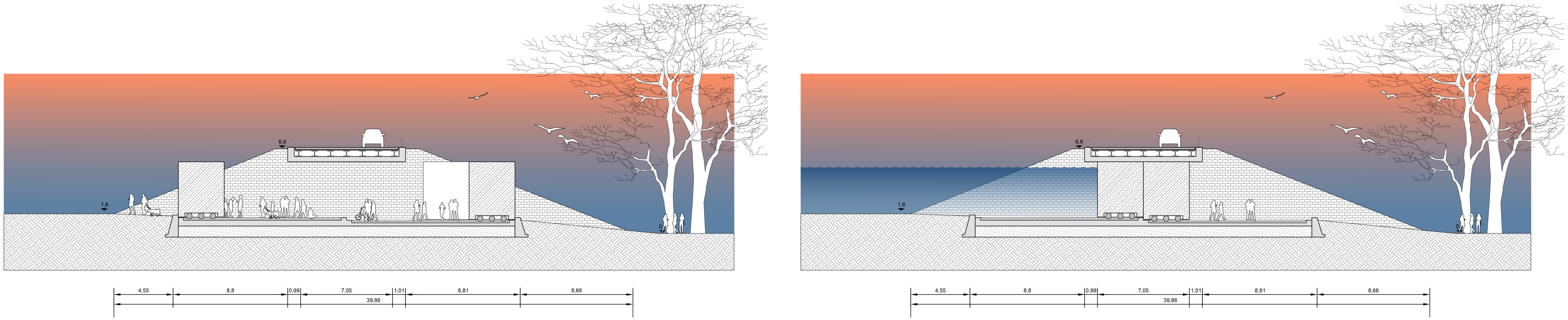
Technical section of the rotatable dike partition



Technical section of the windows in the dike



Technical section of the 'drawbridge' dike partition



Technical section of the sliding flood-gate

APPENDIX IV
Locations of the isometric diagrams for site designs