A lighting infrastructure for data visualisation

on the 3D-printed bridge by MX3D

Master Thesis
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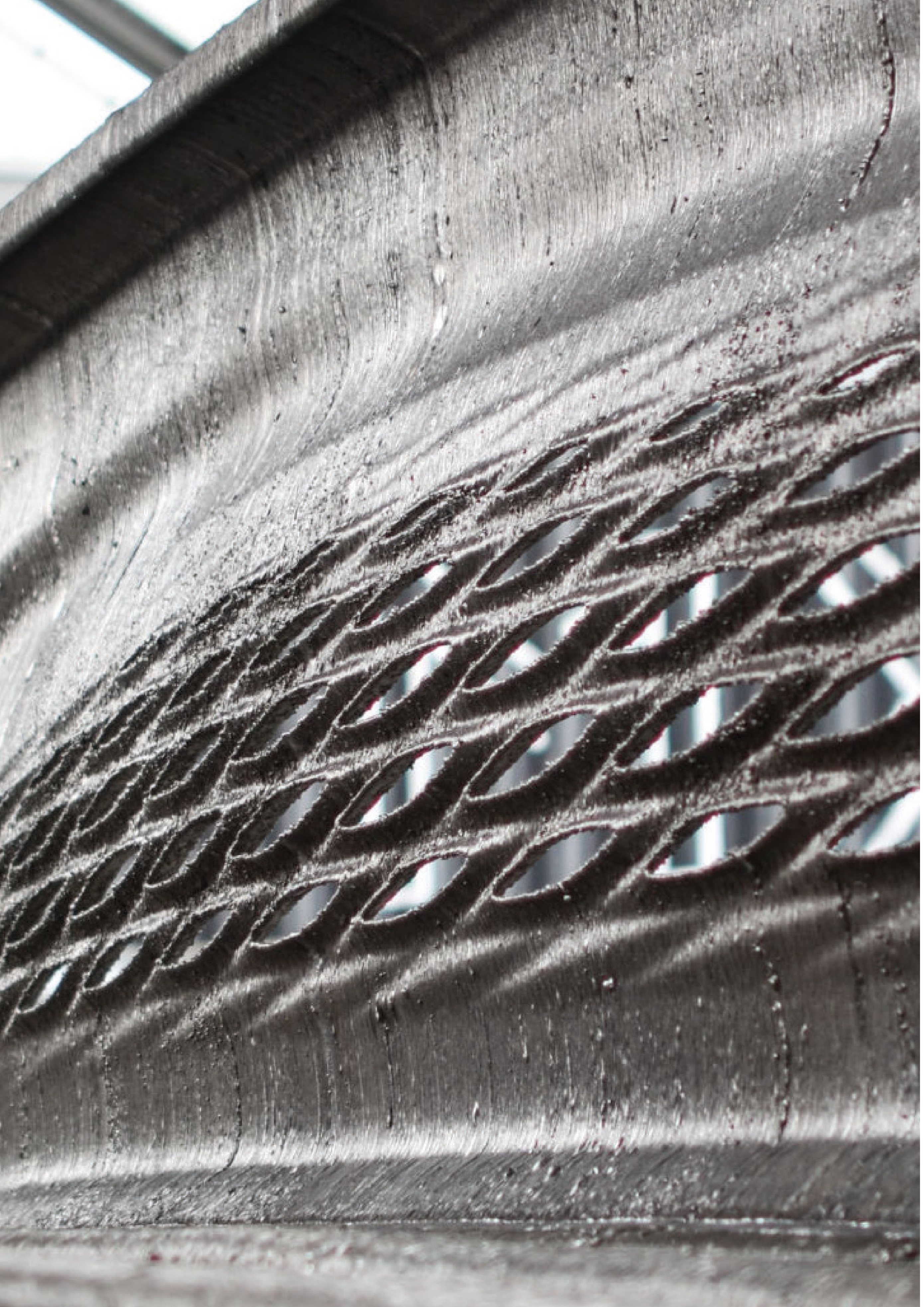

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Figure B.1: *Closeup of the side of the MX3D bridge (MX3D, 2018).*

B Abstract

In 2014, the Joris Laarman lab started developing a new 3D printing technique that led to the creation of MX3D, a consortium companies and research organisations. To showcase their production technique they build the MX3D bridge, which will be equipped with various sensors for technical and contextual analysis of the bridge.
This thesis started with the idea to:

develop a luminous data skin (lighting infrastructure) for the sensor-instrumented 3D-printed stainless steel MX3D bridge to visualise the dynamically generated data,

while taking into account human interaction and experience, urban and architectural design, and smart lighting technologies.
The first step was creating an understanding of the topics: MX3D bridge, data, light, and technology, to gather the knowledge needed to design the lighting infrastructure. Literature research, on-site tests, and interviews were conducted to generate insights.
A valuable function for the lighting was found by using the ViP method. Combining the ViP statement with the data produced by the bridge, resulted in the following purpose definition:

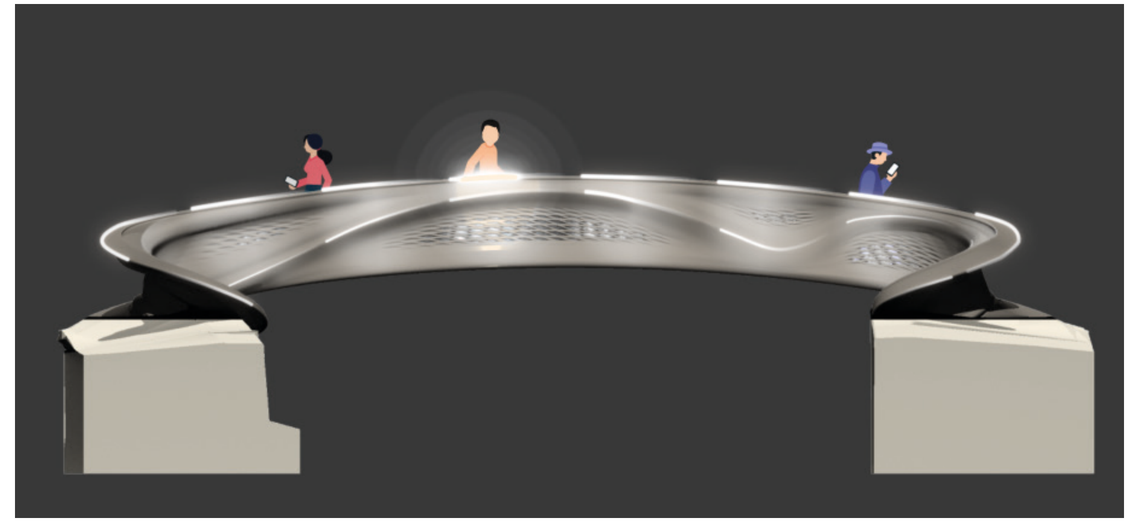
Busyness
- Number of people on the bridge (incl. avg. walking speed and walking direction).
- Number of people crossing the bridge per time period.
- Average time spent on bridge.

Activities
- Current activities (walking, standing still, leaning, jumping).
- Where are people standing on the bridge (currently and aggregated over time)?
- Where are people leaning on the handrail (currently and aggregated over time)?

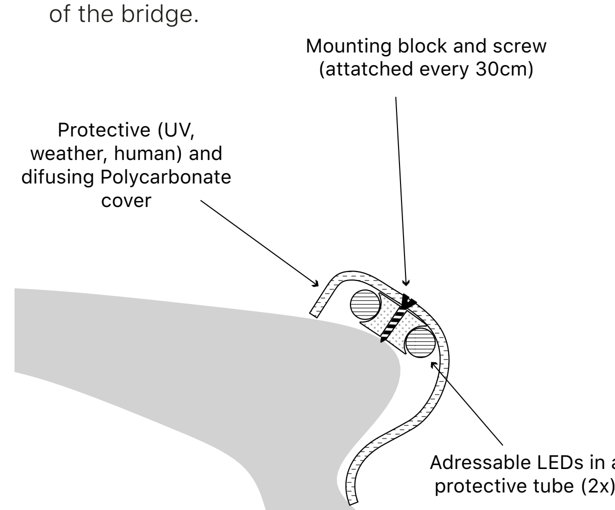
Stopping people on the bridge from standing still too long or at all by making them or the bystanders (subconciously) aware of the problems they are causing with the use of light.

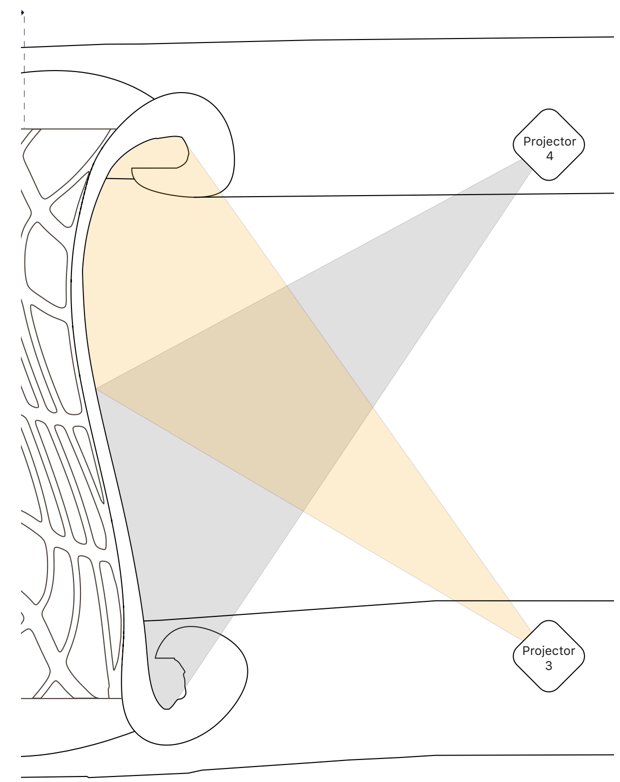
Individual behaviour
- Current location, walking direction, walking speed, and orientation of each individual.
- Current activity (walking, standing still, leaning on handrail).

Development of the lighting infrastructure was split into two parts, an animation (fulfilling the purpose definition), and the physical lighting (enabling the animation to be seen). Literature research, sketches, and prototyping resulted in three animation that ware validated with a user acceptance test. The results let to the final animation which will change using the data from the bridge:



Tests with various light sources let to the final design of the physical lighting:
An addressable LED strip placed on top of the handrail with cover, protecting it from the weather and people while integrating it with the MX3D bridge on multiple levels.
And projection mapping with four outdoor projectors to display the animation onto both sides of the bridge.





C Contents

D Project introduction

This chapter will introduce you to this project, its stakeholders, the assignment, approach, and methods.

Figure D.1: *The MX3D team standing on its 3D-printed bridge (Estes, 2018).*

In 2014, the Joris Laarman lab started developing a 3D printing robot arm to print their sculptural piece Dragon bench. This 3D printing technique had such potential that a separate company was created for further development, MX3D.
MX3D, now a leading consortium of companies and research organisations (Autodesk, AMS Institute, Alan Turing Institute, TU Delft, and others)(Figure D.1), wanted a project for showcasing their new technology. A 3D printed stainless steel bridge over one of the old canals in Amsterdam, connecting the old scenery with modern technology, was found most suitable (Steenhuis, 2018).
During a two year process (ongoing), the bridge was designed and manufactured, pushing current construction and modelling techniques to their limits (Figure D.2).
Due to the new way of manufacturing the bridge, it is largely unknown how it will structurally behave in real life. This is why the smart bridge project was introduced in November 2017 to equipped the bridge with an extensive sensor network, monitoring structural health and use of the bridge (deformations, strains, forces, pedestrian flow, pedestrian behaviour, etc.).

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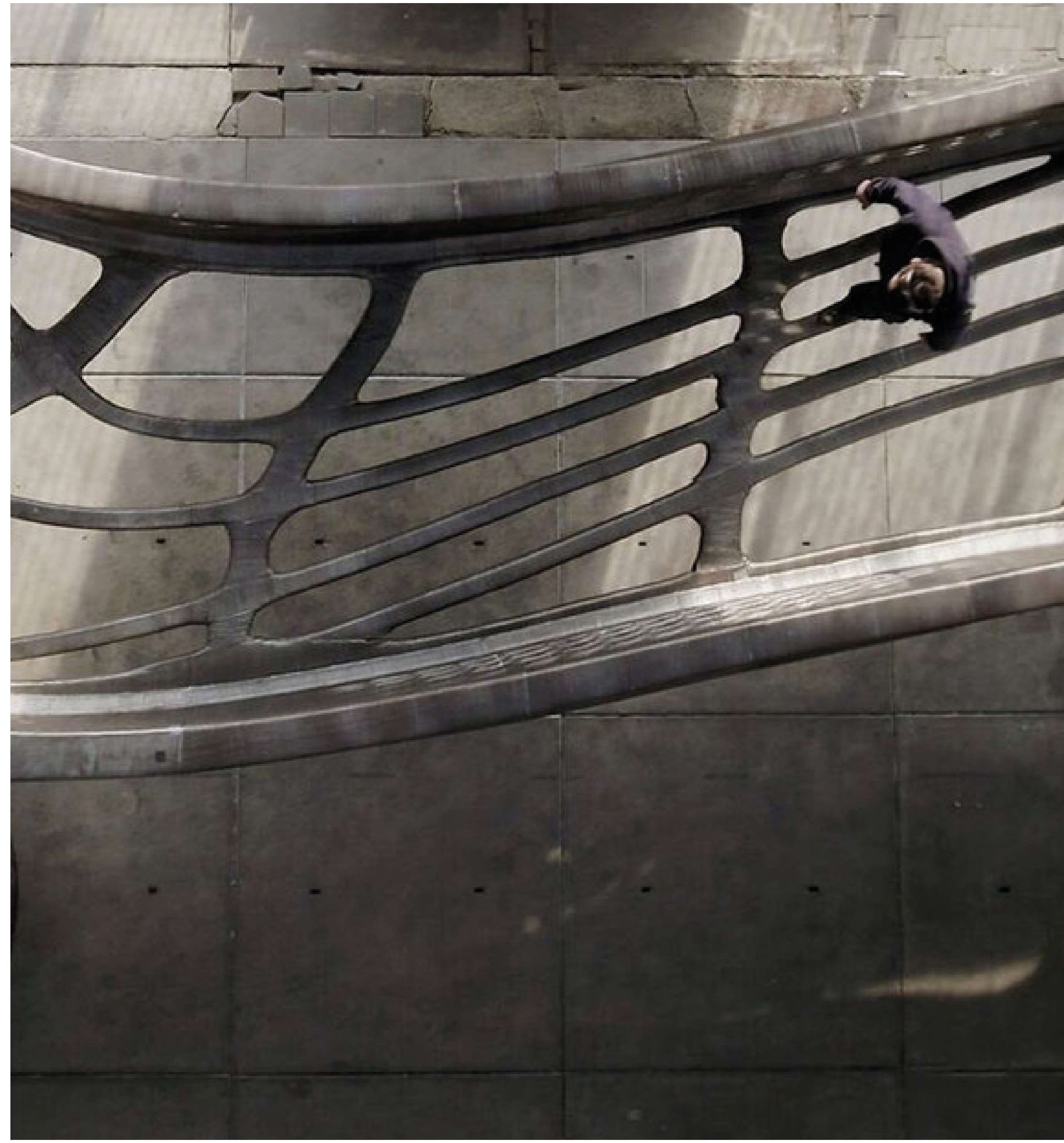


Figure D.2: *Support construction of the MX3D bridge floor (Estes, 2018).*

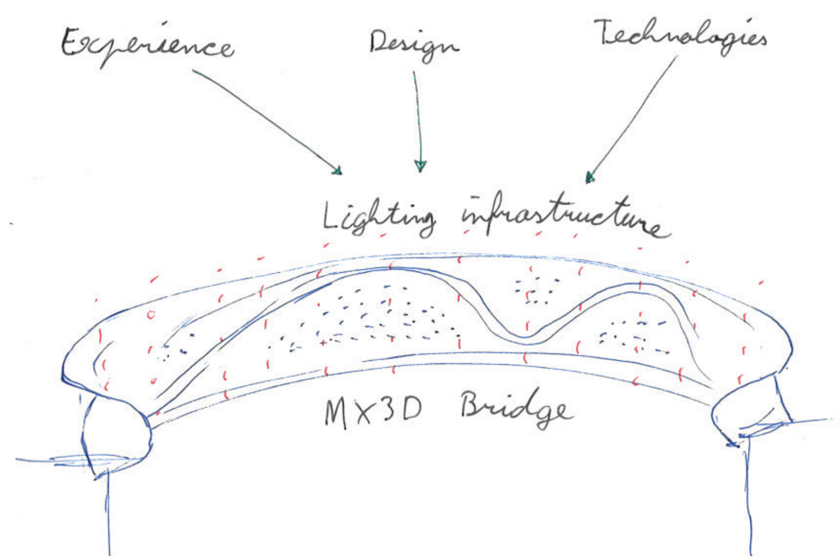
D1 | Assignment

This thesis started with the idea to:

develop a luminous data skin (lighting infrastructure) for the sensor-instrumented 3D-printed stainless steel MX3D bridge to visualise the dynamically generated data,

while taking into account human **interaction** and **experience**, urban and architectural **design**, and smart lighting **technologies**.

The outcome of this thesis will be a proof of concept lighting infrastructure for the MX3D bridge, a context focussed animation to be displayed on this lighting infrastructure. Combined, they will not only create new opportunities to display the increasing amount of data generated in cities (C. Certomà et al., 2017), but could also give people another way of interacting with the structures surrounding them (Seitinger, Perry, & Mitchell, 2009).



D2 | Approach & methods

This thesis will follow the basic design cycle (Roozenburg & Eekels, 1998), where most weight will be in the first section, the discover phase. In this section, literature, contextual, and technical research will be conducted in order to build up knowledge about the subjects. Afterwards, a valuable purpose for the lighting infrastructure will be defined and together with the insights from the first phase, it will form a design brief as a starting point for the design phase. In the design phase the animation and physical lighting infrastructure will be developed in an iterative process whereafter a final concept will emerge that will be evaluated. Figure D.3 represents the structure of this project.

Understanding the MX3D bridge

Analysing the MX3D bridge, context, and sensing of the bridge. This chapter describes what we know about the bridge by analysing different information channels from MX3D. Concluding with the unique aspects of the MX3D bridge on page 35.

Understanding light

Discussing the basics of lighting, lighting in architecture, media architecture, animations, by means of literature research, and field research on visibility of light on the bridge to create constrains for the design of the lighting infrastructure. Concluded with guidelines to design a proper piece of media architecture on page 64.

Understanding data

Analysis on the origin of the bridge data including the sensor network, and availability of the data for this project by means of literature research and interviews. Concluded as insights on data, data flow, sensor network constrains, and a data model on page 86.

Understanding the technology

Analysing the technical parts of a lighting infrastructure and choose the appropriate technologies fitting the MX3D bridge using literature and market research. Concluded with a selection of feasible technologies for the lighting infrastructure on page 102.

Valuable purpose

Using the vision in product design method (Hekkert & van Dijk, 2017) for its human experience centred approach, to define a valuable future context for the design of an animation based on insights on light, data, the bridge, technology, and a trend analysis. Concluded with a valuable purpose for the animation on page 107.

Designing an animation

Define and design of the valuable purpose based animation by sketching, real live test with addressable LED strips, brainstorm sessions, literature research, and interviewing. Concluded with the developed animation that has a valuable contribution to the area around the MX3D bridge, and data controlled on page 148.

Designing the lighting infrastructure

Design of the physical lighting infrastructure to fit the MX3D bridge using real live tests with different lighting technologies, sketches, and brainstorm sessions. Concluding with a fitting lighting solution for the MX3D bridge on page 150.

Evaluation

The animation and physical lighting infrastructure are combined and have a valuable use. This last part reflects on the project, process, and future of this and similar projects. Concluded with recommendations and reflection on page 156.

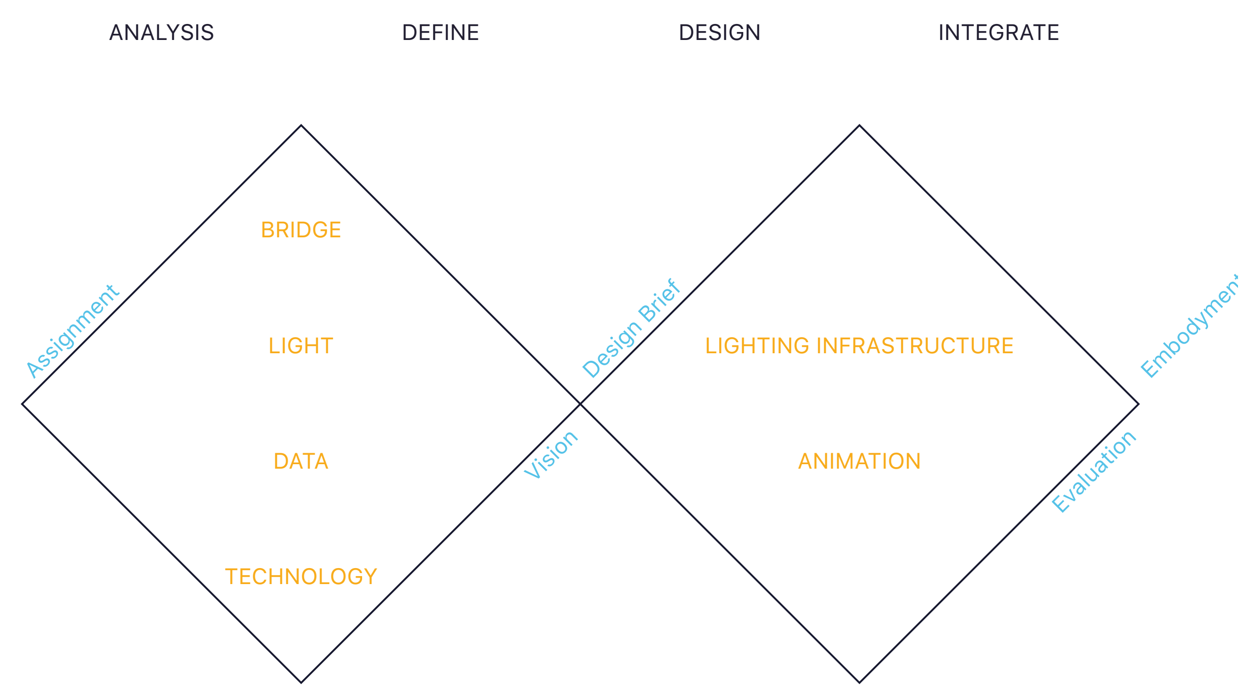


Figure D.3: *Project structure*

E Knowledge areas

The purpose of this chapter is to build up knowledge, understand this knowledge, look at the current state-of-art, find opportunities for the lighting infrastructure. The analysis starts with the MX3D bridge at the core of this thesis to gain an idea of what is being designed for. As the goal is to design a lighting infrastructure, a broad study is conducted on the topic of light, especially on light in architecture, light behaviour on the bridge, and animations. This brings forth the next subject, data. The data generated by the bridge will be analysed from the source, to conclude with a list of available data that can be used to control the lighting infrastructure. Topics that will be discussed are the sensor network, data visualisation, and available data. To enable light and data to come together on the MX3D bridge, different lighting technologies will be discussed and analysed to find the best fitting solution.

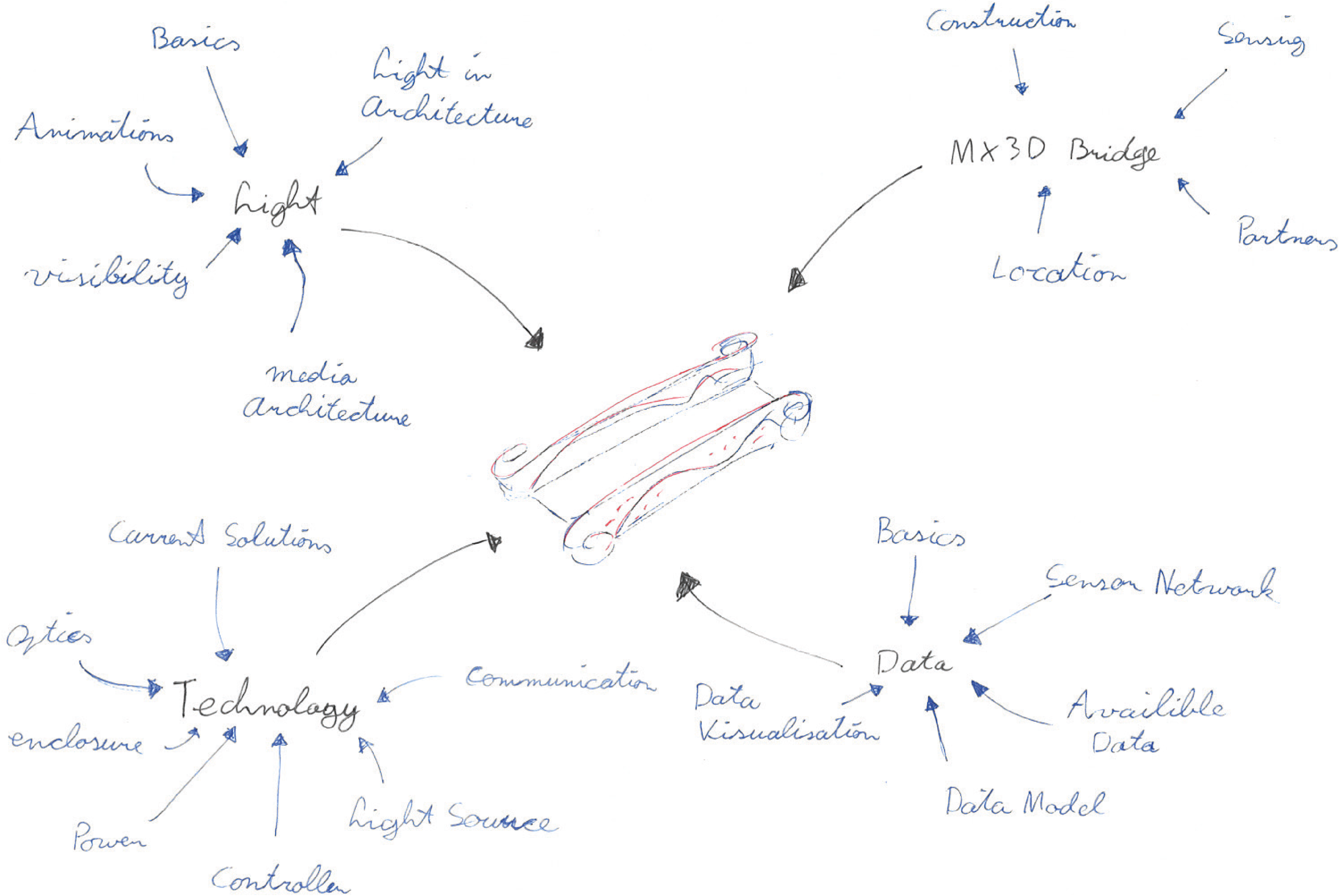


Figure D.4: *Knowledge areas*

E1 | Understanding the bridge

Bridges are among the oldest pieces of infrastructure in human history and play a significant role in modern day transportation. It is a structure built to span physical obstacles with the goal to provide passage over these obstacles and does so without closing the way underneath. It generally consists out of a deck that creates the passage over the obstacle and a way to support this deck. The MX3D bridge however, is unique in its construction and does not support a standard bridge archetype (Figure E.1).
Another way to explain a bridge is to see it as a place of connection. A connection between people, places, cultures and societies. It represents a safe and open passage, and unifies its surroundings.
Understanding the context of the MX3D bridge and the bridge itself, will ensure that a fitting lighting infrastructure can be designed.

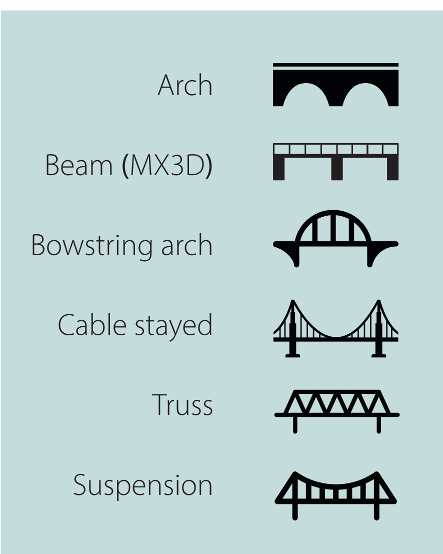
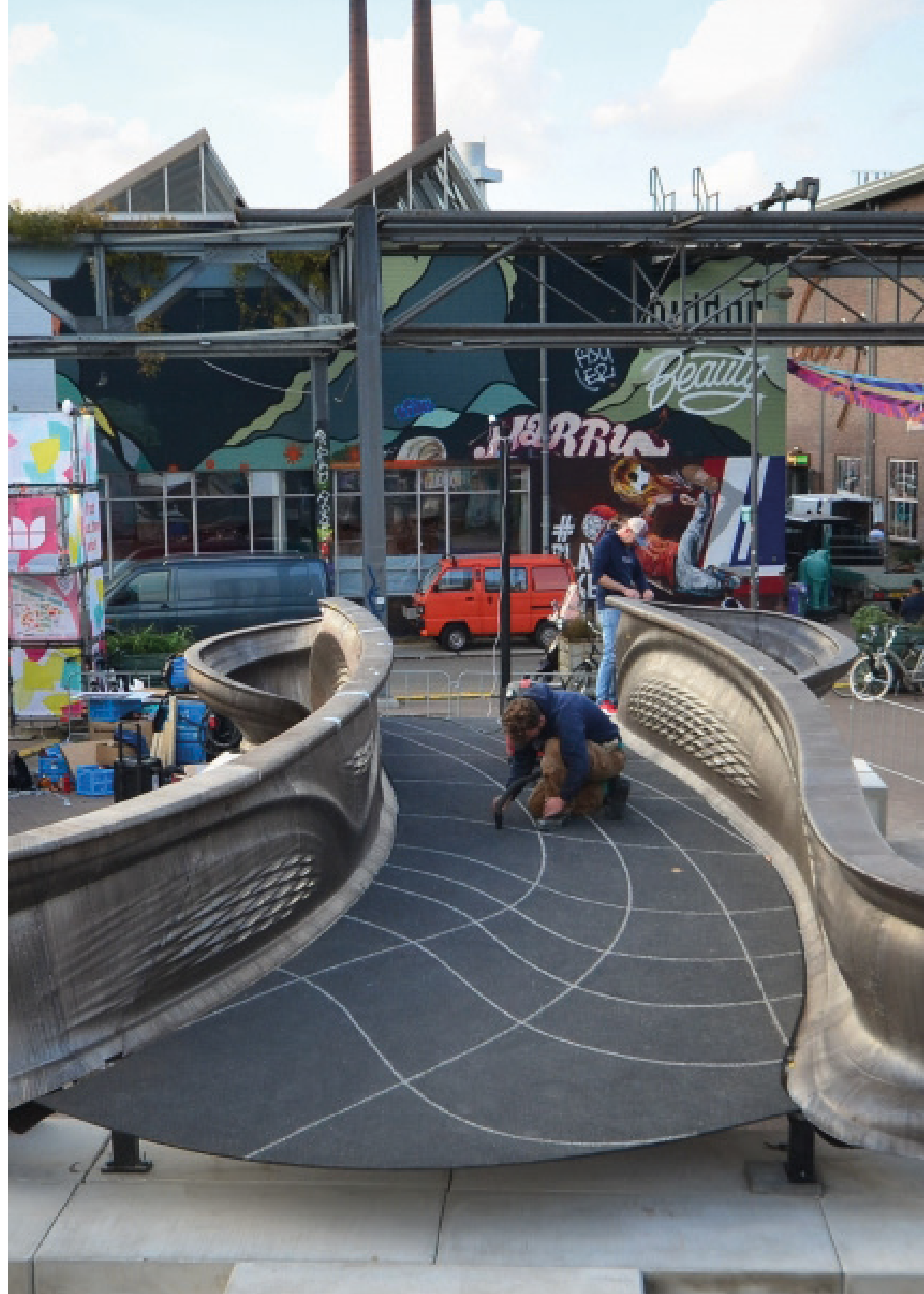


Figure E.1: *Left:Bridge archetypes. Right: Unique MX3D bridge construction (MX3D, 2018).*



E 1.1 | Context - Red light district in Amsterdam

The MX3D bridge will replace the currently installed pedestrian bridge over the Oudezijds Achterburgwal in the old city centre of Amsterdam, connecting the most busy sides of the area, the Oudezijds Achterburgwal and the Stoofsteeg, to allow the crowd to take a shortcut over the canal (Figure E.2).

> ? *What influence does the surrounding have on the MX3D bridge and lighting infrastructure?*

Since 2010, the Amsterdam canal rings, including the Oudezijds achterburgwal, are added to the Unesco heritage list (UNESCO World Heritage Centre, 2010). This centuries old area in Amsterdam houses the Red light district, famous for its prostitution, sex shops, coffeeshops, and cafes.

This area dominated by tourists is one of the biggest sources of hindrances the municipality of Amsterdam is trying to solve for years (Haanen, 2018). Residents of the Oudezijds Achterburgwal for example, experience great nuisance from the abundant amount of tourists (Akkermans, Kloosterman, Knoops, Linden, & Moons, 2017). But, due to the historic state and cramped buildings, it is difficult to alter the area to compensate for the growing amount of tourists. The municipality of Amsterdam has great interest in using modern technologies, like for example Wifi tracking (Hendrikman, 2017), to solve and reduce the nuisance caused by over crowdedness and get better insights into crowd management.

Conclusion

The unique location is a great way for MX3D to promote their bridge, generate and use real time structural and contextual data and find out how projects like these can help the city. However, it also brings difficulties on how to display, gather, and filter data in a crowd. The lighting infrastructure has to cope with these difficulties of which visibility and transfer of information will be most challenging due to the crowdedness.

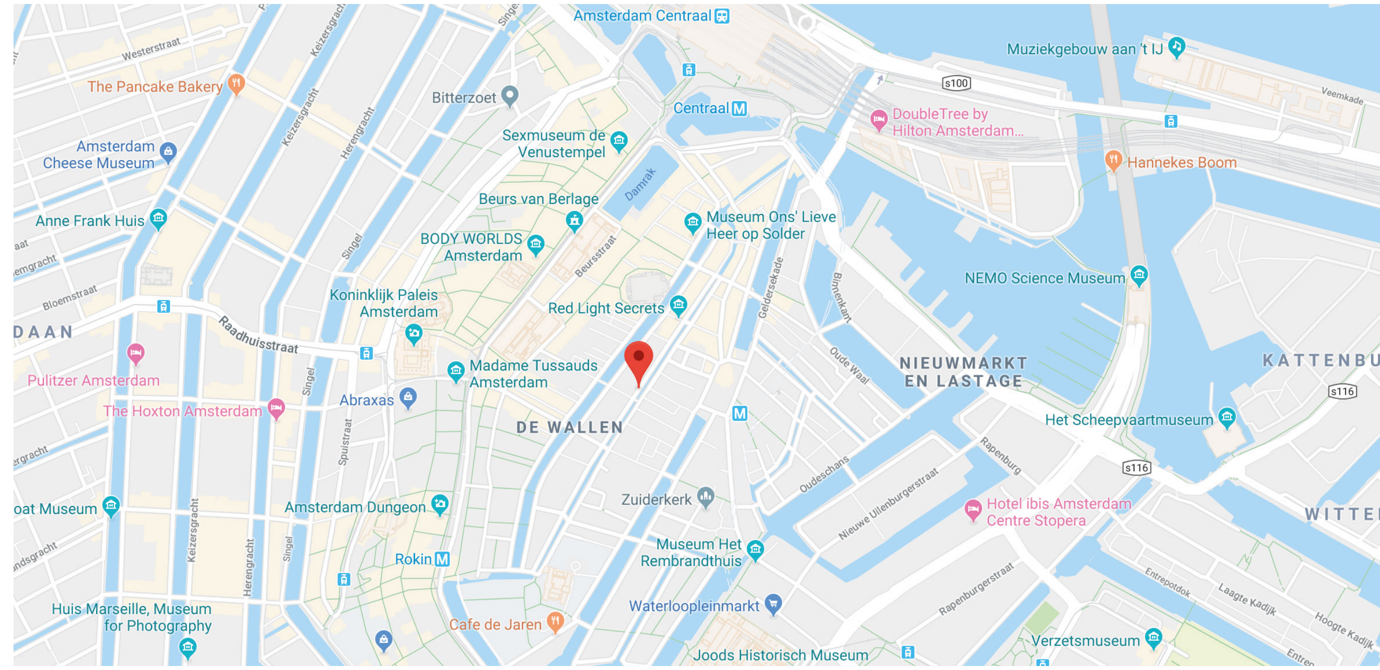


Figure E.2: *Left & top: Location of the MX3D bridge (google, 2018).*

E 1.2 | Project partners

The main partners in the Smart Bridge Project each have their own task and expertise. This chapter will give a clear overview of what role they are playing, how they will contribute to this project, and create a basic understanding of the data and interaction channels.

MX3D develops robotic additive manufacturing technologies, envision automated and autonomous production of computer generated parts and structures to become a standard production method within the next 10 years (MX3D, 2018). Their current production technique consists out of standard robotic arms + standard welding machines + their proprietary software, creating a cheap, modular and scalable production system. Their specific metal 3D printing method is called WAAM (Wire Arc Additive Manufacturing) and is in essence an arc welding machine connected to a three or more axis CNC machine (Williams, et al., 2016). In comparison to other production techniques, MX3D's technique adds the benefit of: freedom of form, virtually infinite build size, optimised shapes for strength, weight and material, cost reduction, and a very short CAD-to-print and print time.

The British national institute for data science founded in 2015 has the mission to change the world for the better by data science research (Alan Turing Institute, 2018). Their role in this project is to design and manage the sensor infrastructure on the bridge. The installation of the sensor infrastructure will be executed by ARUP.

The Institute for Advanced Metropolitan Solutions (or for short AMS institute) is aiming to become an internationally leading institute in metropolitan solution. At AMS institute scientists, engineers, designers, students, companies and professionals work together to design interdisciplinary metropolitan solutions where technology plays a central role ('AMS Institute', 2014). Amsterdam is the home base of AMS and their collaboration resulted already in numerous fruitful projects where data is freely available. In this project they will be a source of city data and knowledge base for data gathering and data displaying.

Autodesk is a large software and technology company based in the USA. They are mostly famous from their CAD software Autocad, but recently also started working on IoT software for building management (Dasher360). A pedestrian bridge in the Pier 9 building in San Francisco (Autodesk's workshop) is equipped with all kinds of sensors to not only measure structural data, but also pedestrian behaviour and other data. By using machine learning algorithms a higher level data set will be created to for example predict patterns, or find new insights. This is the reason they will work closely together with MX3D and the other stakeholders to gain more knowledge about measuring, analysing, and use of (structural) data.

The audience of the MX3D bridge and the lighting infrastructure is defined as the people walking on and in direct eyesight of the bridge. This group of people can directly influence what is happening on and sensed by the bridge. For the greater part, the group of people in the Red light district consists out of tourist, but also locals and commuters.

Figure E.3 shows an overview of what role all the project partners are playing, and how they interact with each other.

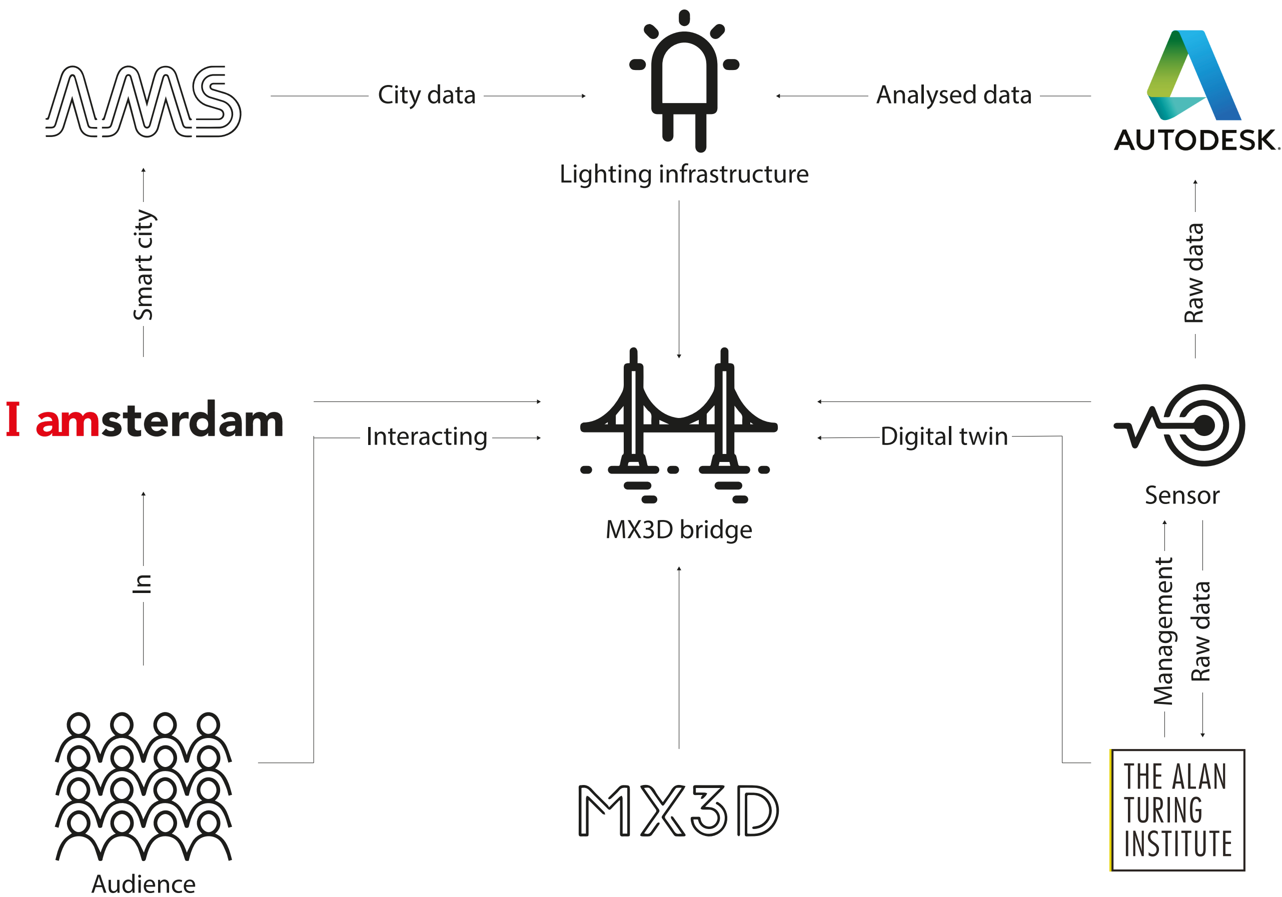


Figure E.3: *The connections between this project, the MX3D bridge, and the different project partners.*

E 1.3 | Construction - The new way of building a bridge

As described in the project introduction the proof of concept and showpiece MX3D bridge will use a new production technique. This however, creates some challenges but also opportunities for implementing a lighting infrastructure when compared to a traditional bridge. Understanding the basic manufacturing process helps designing specifically for this production technique.

> ? *What are the opportunities and challenges for the lighting infrastructure created by this new manufacturing process?*

3D printing or welding?

The building process of the MX3D bridge starts with a big reel of stainless steel wire which is fed into a multi axis robot arm with a MiG welding head (Figure E.4). The robot arm puts layers of molten metal on top of each other according to the 3D model on the computer. This metal 3D printing method is called WAAM (Wire Arc Additive Manufacturing) and is in essence an arc welding machine connected to a three or more axis CNC machine (Williams, et al., 2016).

This relatively new manufacturing technique creates a shell (Figure E.4) instead of a solid cross-section, which results in faster print times, less material usage, less weight, and the possibility to feed cables through the structure.

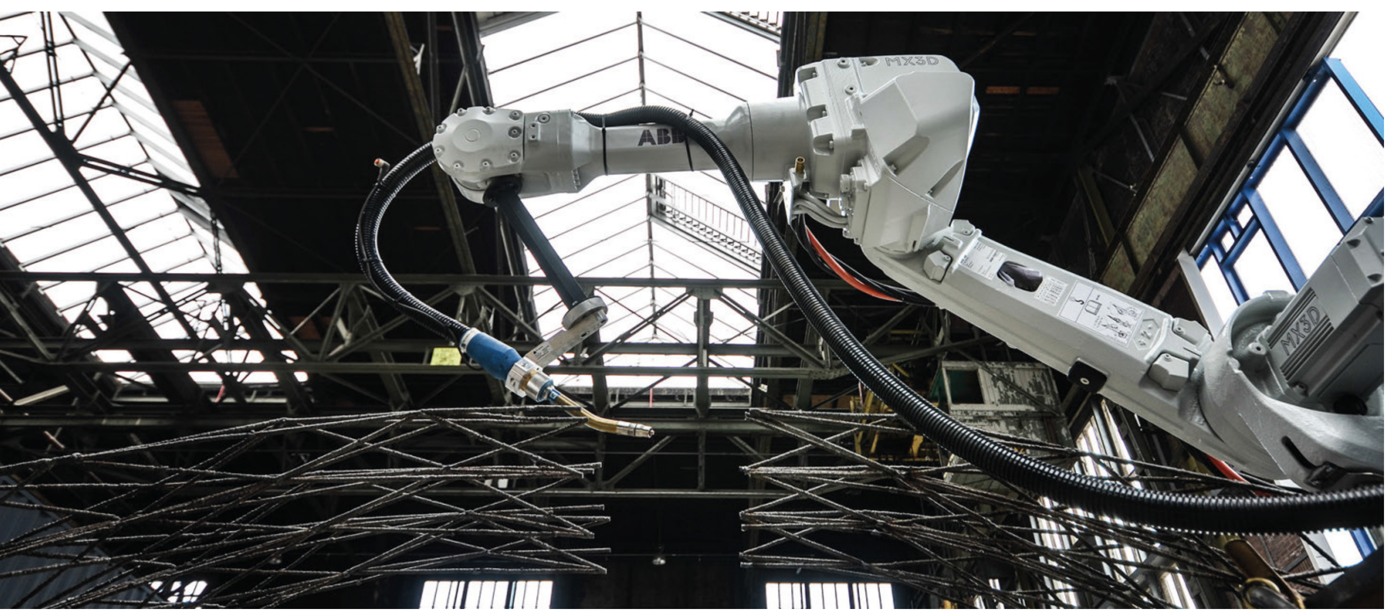


Figure E.4: *Left : MiG welding robot. Top: Shell. Bottom: Weliding lines.*

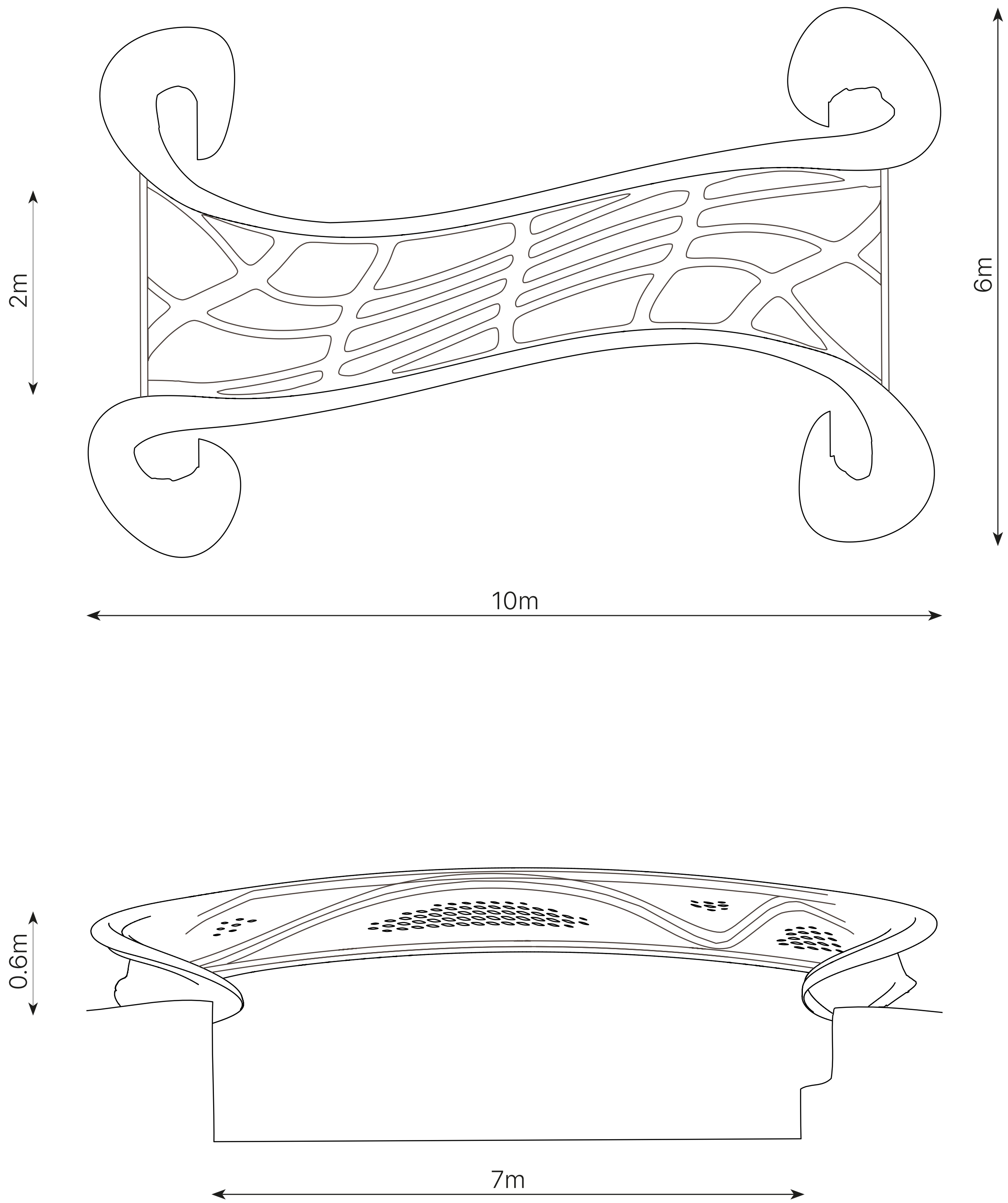


Figure E.5: *Geometry of the MX3D bridge.*

Due to cost and complexity, the MX3D bridge is not manufactured in one go, which was the initial goal, but consist out of multiple segments welded together (Figure E.4). What makes this bridge unique is the fact that after welding it is one piece out of one material. There are no screws, adhesives or other fasteners used to keep the bridge together. In future projects, it may be possible to 3D print a full structure/bridge on sight, in one step.

Due to the design-while-building approach of the MX3D bridge, there is not much or no thought given upfront to non core elements like the lighting infrastructure, sensor network, or even floor covering. The design of this first version of the bridge is solely focussed on production of the bridge. Manufacturing of the bridge happened at the MX3D headquarters in the MDSN werf Amsterdam.

Conclusion

The completed one-piece MX3D bridge (Figure E.5) is an amazing combination of engineering and design, demanding the maximum possible from new production technique by MX3D. The hollow structure of the bridge can be used to route cables, hiding them from plane sight. However, during the manufacturing of the bridge, the installation of the sensor network and lighting infrastructure were not taken into account, and are more an afterthought which makes proper integration more difficult. The fact that the whole structure is one piece could also make installation of the lighting infrastructure more difficult, as things like cables cannot be installed during the build process like in subassemblies.

Now that it is known what the MX3D bridge is and why it is special, the next chapter will take this a step further and give an introduction into the smart properties of the bridge.

E 1.4 | Sensors on the bridge - The smart bridge

As described in the project introduction, the MX3D bridge is in the centre of the Smart bridge project, and will be equipped with sensors. Why these sensors are on the bridge will be discussed in this chapter.

? *Why does the bridge have sensors?*
? *What types of data are being produced?*

The data on coming from the MX3D bridge has multiple uses that can be divided into two categories, data with a technical uses, and data with contextual uses.

Technical data

Safety, material properties & manufacuting optimisation
When building anything, from a smartphone to a skyscraper (or bridge), it is important to know how the materials you made your product from will behave under different circumstances. When the appropriate material properties are know, it is for example possible to calculate when a product will fail, or optimise the shape for maximum strength and minimum weight.
As the MX3D bridge is made with a new manufacturing method, it is unknown how the resulting structure will behave in real life. Computer models have been used to design the shape of the bridge so it is strong enough (Joris Laarman, 2018), and give estimates on its behaviour when in use, however these models use simplified representations of the bridge. The real 3D printed bridge has flaws; human errors, shape differences, no uniform material, etc. To validate the integrity of the bride, and get a better understanding of the 3D printing technique, the bridge will be equipped with sensors to measure its real life behaviour in a real environment.
The main sensors used on the MX3D bridge can measure:

- Local acceleration (movement)
- Local strain (displacement)
- Weight distribution (location)

During use of the bridge, when for example an average of 10 people are walking on it, it will deform slightly under the load of this crowd (displacement). Due to the impulses created by the walking of the crowd, the bridge will vibrate (movement). When there are more people on one side of the bridge, there will also be a higher down force on that side (location + displacement). This data will create insights into the material en structural properties of the bridge under certain physical forces, which is interesting for the 3D printing production process.

Contextual data

The three sensors mentioned, plus other sensors, generate data that will be used for structural analysis by the Alan Turing Institute, and future projects.
Analysing this bridge behaviour data will also create insights on what is happening with, on, and around the MX3D bridge (context). This extra step of data analysis is unique and the smart MX3D bridge will be one of the first cases were this data is extracted from architecture.
For example, in the event of one person setting a step on the bridge, it is in theory possible to recognise when that person is putting his feet on the bridge (movement), how heavy that person is (displacement), and where that persons feet touches the bridge (location). Figure E.6 shows what data will be produced from the main sensors during this event. As the MX3D bridge will be equipped with many sensors, there will be a fast amount of different events to find, recognise, and create a digital representation of what is happening on and around the bridge.

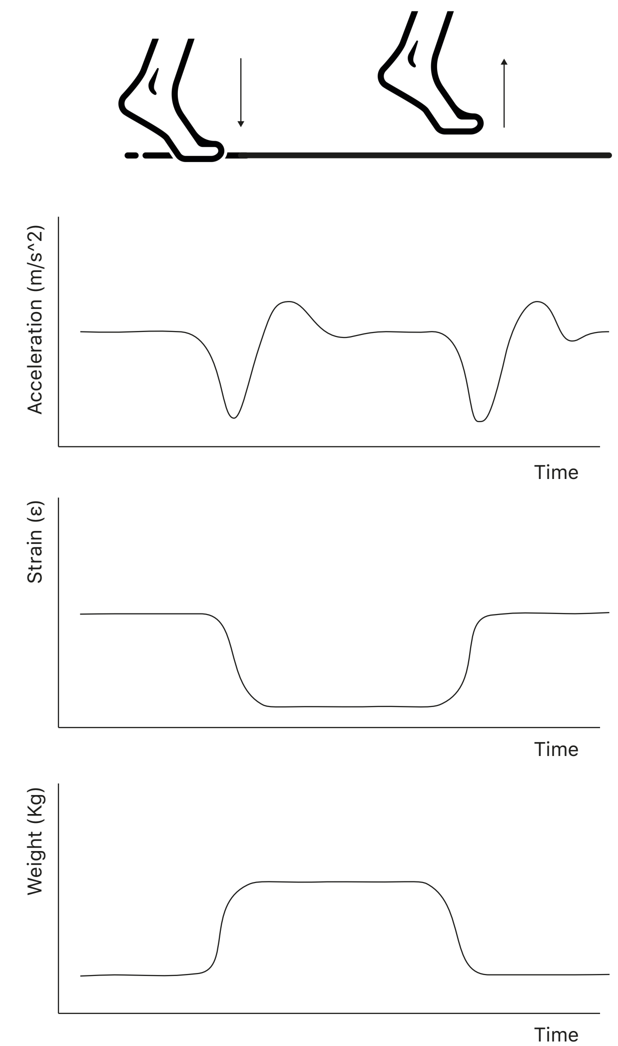


Figure E.6: *Sensor data example.*

Conclusion

The fact that the MX3D bridge has a much higher sensor density than normally used for structural analysis, creates more data to use. On top of that, the extra analysis step creates contextual, more humanised data that give insights on what is happening on and around the bridge. This last type of data will be of most interest due to its unexplored opportunities, and will be explored further.

E 1.5 | Summary

The MX3D bridge is a unique piece of engineering, art, and technology, placed in one of the busiest spots in the Netherlands. Designing a lighting infrastructure for this showpiece is challenging, yet also a great opportunity to better the area and create meaningful use for the data generated by the bridge. The next chapter will start with research on light, in specific light in architecture and light on the bridge.

Figure E.7: *A steel deck will cover the curved supports on the bottom of the bridge (Estes, 2018).*

Design insight

Project partners

- *The most interesting partner is Autodesk, as they provide the data collection, contextual analysis, digital tools, and have experience from their own smart bridge.*

Context

- *Unique location requires a unique use of data and lighting.*
- *Crowdedness should be taken into account.*

Construction

- *It is difficult to mount parts on the rough and curved surface of the bridge.*
- *The lighting infrastructure should not alter the design of the MX3D bridge as the bridge itself is the showpiece.*

Sensors on the bridge

- *Contextual data most interesting.*

E2 | Understanding light

This chapter discusses aspects of light in general, light in architecture, animations, and visibility of light on the MX3D bridge. Various questions regarding light are answered to form design constrains and insights.

? *What types of light does a lighting scene consist out of?*

Figure E.8: *The Galleria in South Korea by UN Studio (UNStudio, 2018)*

E 2.1 | Basics of light

Designing a lighting infrastructure requires the knowledge of how to form a lighting scene out of basic light elements. These basic elements of light perceivable by humans are clearly defined by Richard Kelly in three terms.

? *What does a lighting scene consist out of?*

Light types by Richard Kelly

Ambient luminescence

This can be explained as the light around us. It is unidirectional, indirect, ambient, very good to bring colours forward, flattening, and creates no field of depth. This is the light that makes everything visible.

Focal glow

Focal glow is also known as spotlights. It draws attention, is directional, separates the important from the unimportant, creates sharp drop shadows, and creates depth. This light makes you look at something.

Play of brilliants.

The twinkling of a diamond in the sun would be a good description of the light that is also known as highlights. It is optically stimulating, directional focussed, playful, attention catching, and creates a high gloss effect. This light is interesting to look at.

According to Richard Kelly; "Visual beauty is perceived by an interplay of all three kinds of light, with one element generally playing a prominent role in the total composition" (Maile Petty, 2007).

Conclusion

The devision of light into three types (Figure E.9) creates a better understanding of what type of lights need to be used in order to get the desired effect and proper integration into the structure and surroundings. Using lights that produce focal glow and play of brilliance seems most interesting to display data due to their ability to show or highlight details. Ambient luminescence is already present on the bridge in the form of street lighting, signs, and other wide emitting lighting in the surroundings and is therefore not necessary to implement on the MX3D bridge.

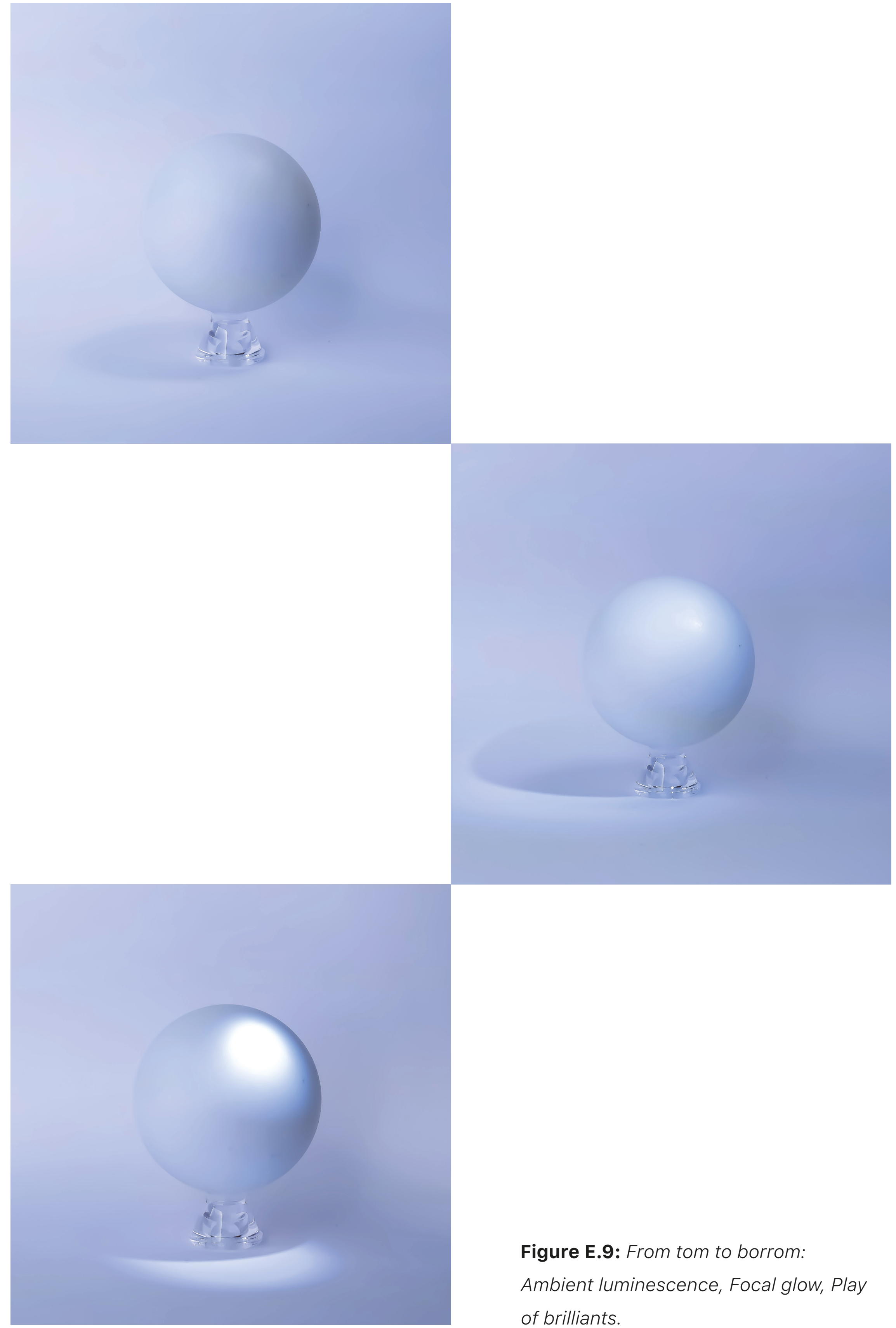


Figure E.9: *From tom to borrom: Ambient luminescence, Focal glow, Play of brilliants.*

E 2.2 | Lighting in architecture

Finding the underlaying purpose and function of lighting on bridges and other architectural structures will define design constrains for the bridge lighting infrastructure.

? *How is light used in architecture?*

Approach

Literature research was done on the topic of lighting in and on buildings, bridges, and other structures to gain an overall understanding of how light is used in architecture. For all uses, an example of a bridge was found to bring the results into the context of this thesis.

Analysis

The first and main reason a bridge or structure needs lighting is safety. Participants in traffic need to see where they are going and what is happening around them. Humans sense their environment in traffic with mainly their eyes which need light to function properly. During daytime this is of course no problem, but during nighttime artificial light is a must.

Light can also be used to emphasise the shape, surface, colours, and contours of an architectural structure. This type of lighting is often designed by the architect and is part of the holistic design of the structure. On bridges this often translates to surface illumination (grazing), (concealed) linear lighting, and spotlights. These lights are mostly lighting the bottom of the bridge, big parts or pillars, handrails and characterising features (Kruizinga, 2018).

Combining functional and aesthetic lighting is also done but mostly not used exclusively. It adds more complexity to the lighting and it is often accompanied by more functional lighting later on. For example on the Neskio bridge in Amsterdam where the 2in1 lighting solution did not produce enough light and needed to be accompanied with more street lighting (Figure E.10)(van den Dobbelsteen, 2013).

Figure E.10: *Nescio bridge is being equiped with extra street lighting (van den Dobbelsteen, 2013).*

Figure E.11: *The city bridge of Brugg during day and night time ('Beleuchtung Mülimattsteg & Geländer', 2018)*

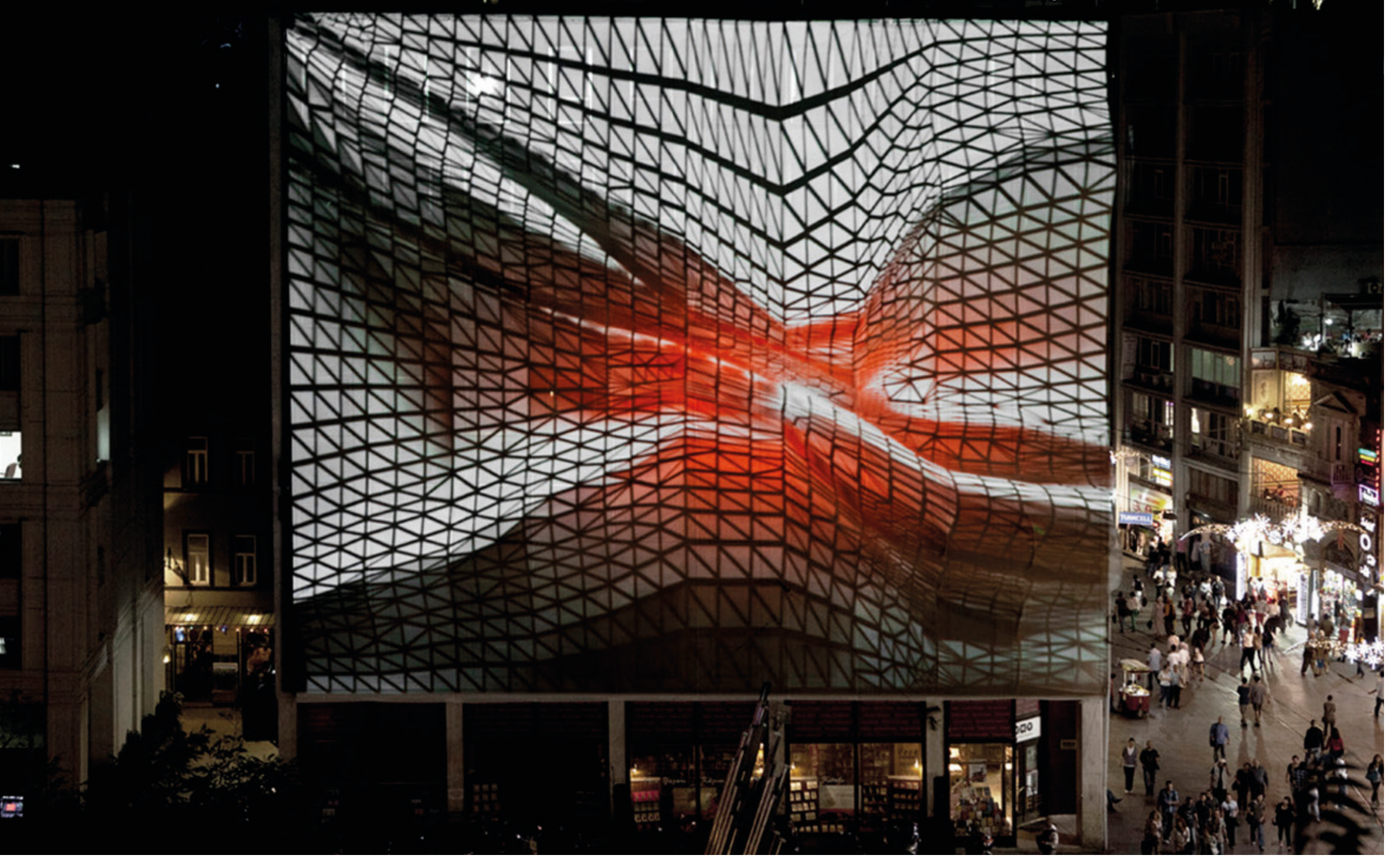
Light is sometimes used to create new patterns to extend or alter the normal architectural features. For example the city bridge of Brugg (Swiss) where they used lighting to create a new shape (illusion) on the deck during night time (Figure E.11), The Galleria in South Korea (Figure E.8), or as in Figure E.12 ('Beleuchtung Mülimattsteg & Geländer', 2018).

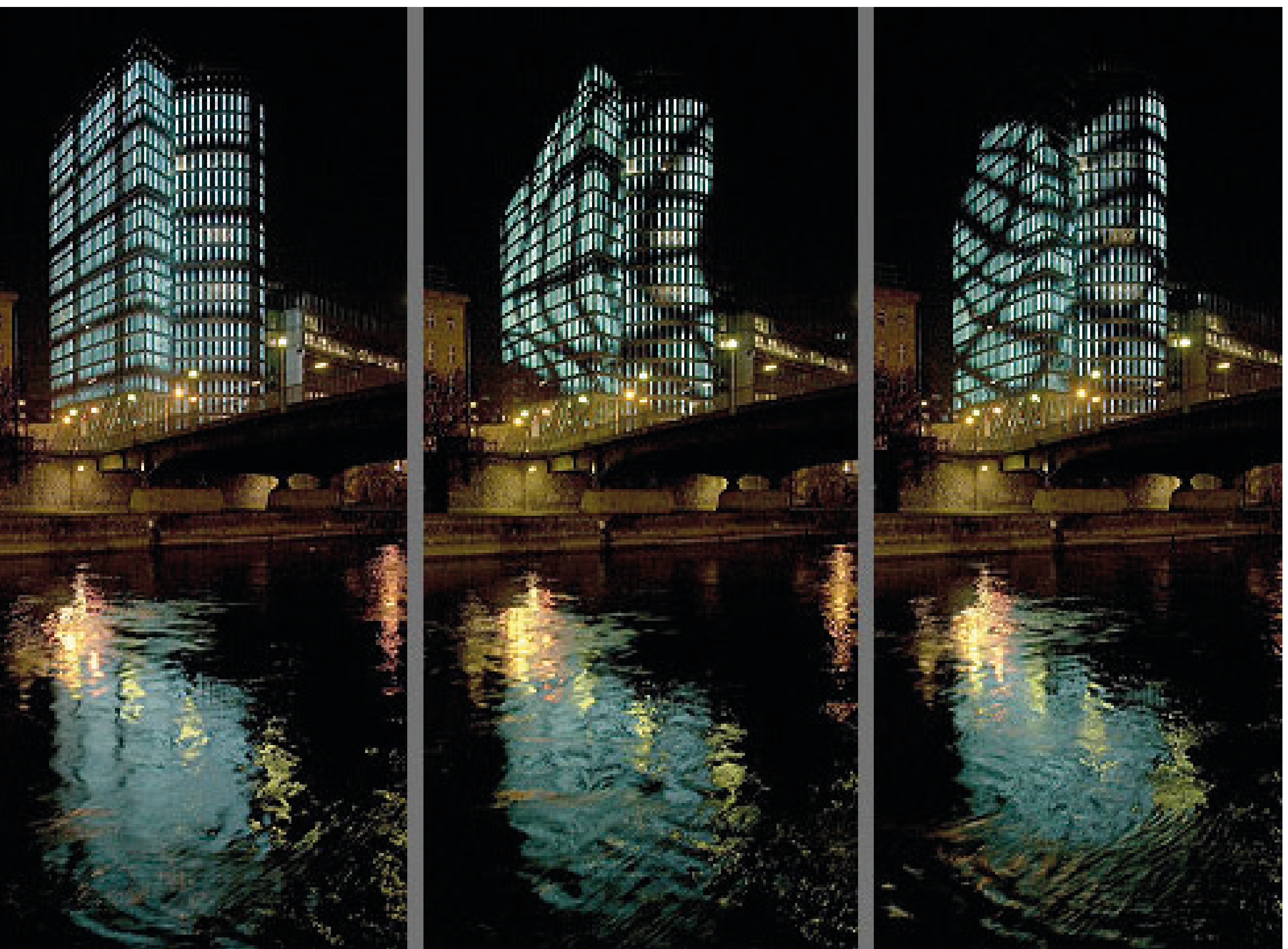
At last there are special events where the structure is used as canvas or screen. Specially installed show lighting is often used during events like New Year's Eve, concerts, and other festivities. The Erasmus bridge in Rotterdam is for example used as canvas during New Year's Eve and the boat festival. It is also used as a billboard once in a while, to display upcoming events in the city.

Conclusion

Lighting in architecture can be categorised into three purposes. The first and only essential purpose is **safety**, the ability to see where you are (going to). Secondly light can be used to emphasise or alter the shape of the structure. This has an **aesthetic** purpose. At last there is a **functional** purpose, where light is used to transfer information and influence people.

For this project, functional lighting is of most interest as this is a mostly unexplored area, especially when combined with real time data. For this reason, further research is needed on this topic (next chapter). Aesthetics of the lighting infrastructure are important for the coherence with the MX3D bridge, and should also play a role in the design of the lighting infrastructure.





E 2.3 | Media architecture

Recent technologies made it possible to separate the facade of a building from the load bearing structure creating an extra skin. This makes it possible for all sorts of external active media like displays and screens to be placed on facades (Moere & Wouters, 2012). Not only buildings, but also other public spaces are able to show more and more information, for example in public transport or even on statues (Halskov & Dalsgaard, 2011). The term media architecture encompasses all these types of media used in various public spaces, structures, and more. As the MX3D bridge seems to have the ingredients to be a piece of media architecture, exploring this topic will create better guidelines to design a proper lighting infrastructure.

? *What makes something media architecture?*
? *What are the benefits of media architecture above conventional methods?*
? *How can the MX3D bridge lighting infrastructure become a piece of media architecture?*

Creating media architecture

The upcoming trend to equip various structures both on the in and outside with (inter)active media opens up the opportunity to use everything as a digital canvas and create very promising cultural and social values that have yet to be exploited (Garcia, 2007). This is also directly the problem with media architecture, it is not a well defined and explored area. Most media architecture projects are conceptual, too artistic, only focussed on advertisement, or lack in depth interaction with the audience.

The term, media architecture encompasses different levels of integration, explaining the contextual perspectives (the parts it consists out of) gives a better understanding of what media architecture actually is.

The first perspective of media architecture is the environment, the Oudezijds Achterburgwal for this project. The environment is not only materialistic (buildings, nature, etc.), but also contains non tangible elements like culture, society, and behaviour.

Figure E.12: *Top: Refik Anadol, "Augmented Structures v1.0: Acoustic Formations/Istiklal Street," 2011. | Photo: Courtesy of the artist.*

The second perspective is the content that is displayed. Which consists out of a messenger (LEDs, displays, etc.), and the message(s) with their intended meaning.
At last there is the carrier, also known as the structure. In this case the MX3D bridge. As the carrier is a big part of media architecture it has great influence on the perception of the content and of course the environment (Moere & Wouters, 2012).

Integration

A vital property of media architecture is integration with the structure, were the level of integration directly influences the perception of the media and structure. The main part of integration comes from the spatial properties of the media (2D, 2.5D, 3D). Not only the shape, but also the transparency and translucency of the media have great influence (Tscherteu, 2008). This means, both media and structure need to be part of each other to form a symbiosis.
For a piece of media architecture to fulfil its purpose over a longer period of time, several criteria need to be met according to recent research (Moere & Wouters, 2012). Media architecture should aim for a sensitivity towards the social-cultural aspects in its environment, an architectural and societal integration, and provide qualitative content.

Conclusion

The composition of the bridge lighting infrastructure (environment, content, carrier)(Figure E.13) together with the interaction it elicits, makes it a piece of media architecture.
For the lighting infrastructure to be perceived and experienced correctly, the content should be qualitative and of social-cultural influence. As this is mostly not achieved in the given examples, there is an opportunity to give the bridge lighting infrastructure a real valuable purpose and have social influence, making it even more unique. Using a human centred design approach (ViP), it is expected to find this valuable purpose. On top of that, the lighting infrastructure should be integrated with both carrier and environment to be perceived as a whole and should be made easy to understand for the audience. As the bridge produces data in real time, using this data leads to a dynamic visualisation, which will be discussed in the next chapter.

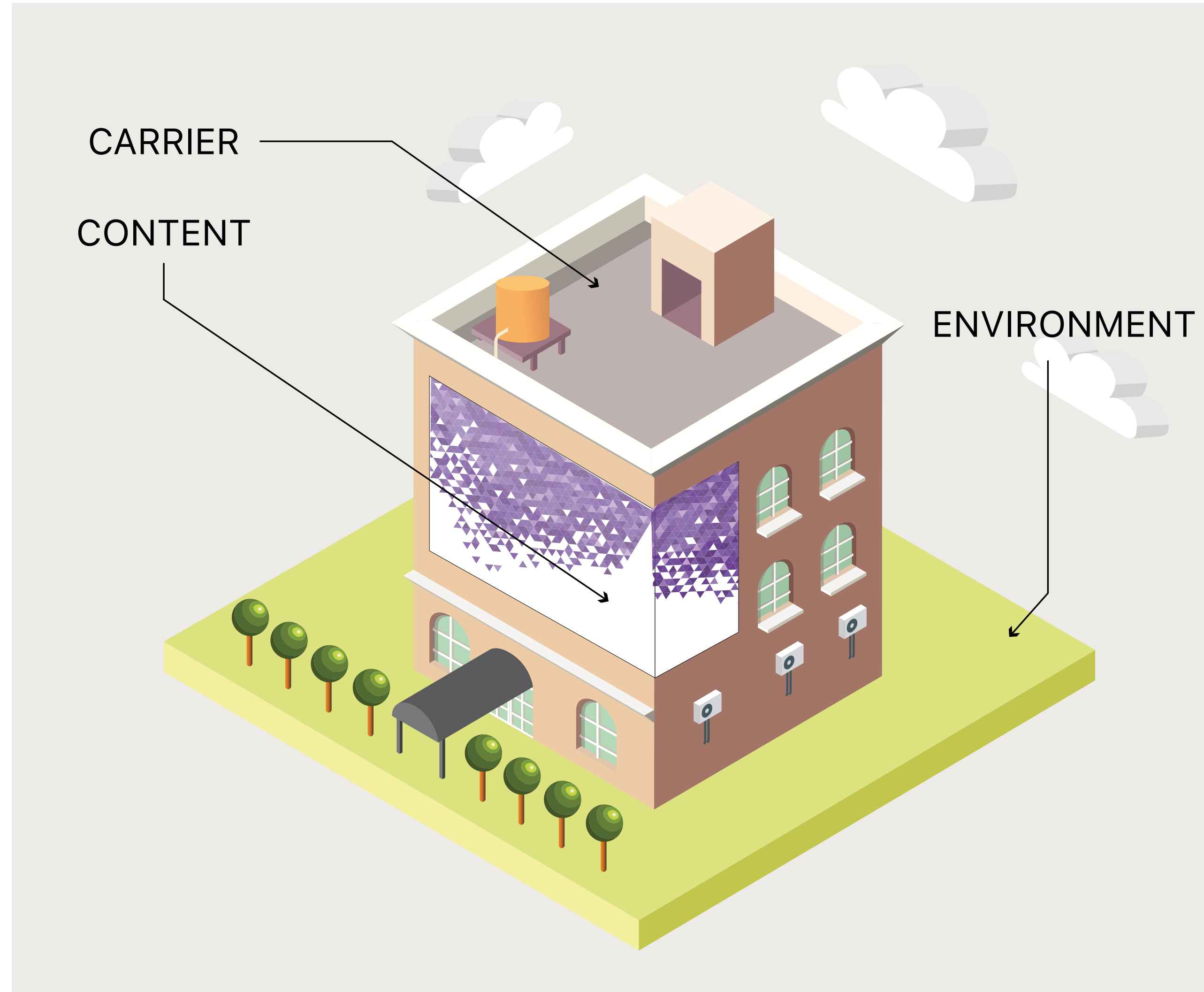


Figure E.13: *Environment, content, and carrier.*

E 2.4 | Animations - moving information

Humans are naturally attracted by movement because it creates a pleasurable visual sensation. Animations therefore makes us feel comfortable and makes a space we are standing in more natural and attractive (Koerner, 2017). Changing light parameters like colour, intensity, and shape over time automatically forms an animation, and by adding feedback, an interactive lighting infrastructure can be created. These parameters can be driven by the data generated by the MX3D bridge, creating information visualisations.

? *What are the caveats in using animations for information visualisation?*

Aesthetics vs information

In standard information visualisation (graphs, numbers, etc), aesthetics can be considered a bi-product, or bonus while transferring the right information is the main purpose. However, in ambient information visualisation, aesthetics is considered a primary property (Skog, Ljungblad, & Holmquist, 2003). This does not mean an ambient display is not able to transfer information clearly, but it will cause uncertainties if the information is interpreted by the audience correctly. If either the context, content, or carrier in the lighting infrastructure changes, reevaluation of the interpretation by the audience is required.

Resolution

The resolution of the information being transferred is directly dependant on both the physical resolution of the lighting infrastructure, and the resolution of the displayed content (Informative Art, 2003). For example when the battery icon on your phone is red, you know it's almost empty but not the exact percentage.
A higher physical resolution enhances the flexibility of the display, and increases the complexity of the information that can be shown (Skog, Ljungblad, & Holmquist, 2003). However, the perceived resolution is dependent on the "pixel" density, the distance between the lighting infrastructure and the observer (stand close or far away to your tv screen), and the resolution of the content. As the audience walks towards the bridge, this distance decreases and so does the perceived resolution (you can see the pixels). Standing far away from the light source also decreases perceived resolution (it gets blurry). Generating a light mood, like hot (red), warm (orange), or cold (blue), for far away observation of the lighting infrastructure, ensures some lower resolution information can still be transferred clearly. Increasing the pixel density will overcome this problem for close range observation.

Interaction

To create a good lighting based interaction, "Users should be able to get a sense of the overall information space with a quick glance" (Vogel & Balakrishnan, 2004). This means the time to make people understand your message is very short and the message to be transferred should not be too complex. According to Holmquist & Skog (2003), messages transferred by light can have one of the following functions or interactions:

- *Functional: the right light at the right place and time*
- *Delight: enrich human environments*
- *Content: portal to the digital world (ambient information).*

Conclusion

Animating with light to visualise information and transfer a message can be achieved for a range of distances between the observer and the source, provided that the resolution is either hight enough for up-close observation (pixel based), or clearly presented with a lower resolution at longer distances (ambient light).
During the design of an animation, a balance needs to be found between information clarity, and aesthetics as these two oppose each other. The designed animation should be understandable with a quick glance, and evaluated on interpretation and correct understanding by the audience. The sole purpose of the animation is to create a portal to the data from the bridge and should enhance the surrounding environment.
The next chapter will make sure the animation will be visible for the intended audience by finding the best spot to place the lighting infrastructure.

E 2.5 | Visibility of light on the bridge - obstacles

This chapter will dive into the physical aspects of visibility of the bridge and the lighting infrastructure. It will include on site field research and an analysis to find the best places to install the lighting infrastructure on the MX3D bridge.

? *What spots on the MX3D bridge makes the lighting infrastructure most legible?*

Objective

The goal of this field research was to find out the best spot to place the lighting infrastructure and create a boundary from what range and place the lighting infrastructure and bridge could be seen.

Approach

Systematically photographing the bridge currently installed on the Oudezijds Achterburgwal in the centre of the frame with a digital camera created detailed images from a human perspective. A vector map (CADMAPPER, 2018) shows a detailed representation of the Oudezijds Achterburgwal area on which the test points are visualised (Figure E.17). All test points include a brightness value measured by a lux meter.

The bridge was separated into six parts (handrail, inside, outside, underside, deck, and opposite quayside) that were individually rated on visibility (0-100%, steps of 5%) from every test point (Table 1.1) as in Figure E.15.

Analysing the pictures taken closest to the bridge during evening hours (point H to I) in color.adobe.com colour analyser, resulted in a colour pallet with the most prominent colours.

Figure E.14: *People standing still on the bridge in the Oudezijds Achterburgwal.*

Analysis

Physical obstruction

The field research brought to light a lot of physical obstacles. Every 16 meters a tree is present next to the water on both sides north of the bridge and on one side (Oudezijds Voorburgwal side) of the water on the South side of the bridge, obstructing view to the bridge from 0 to 10 meters height.

The bridge quickly becomes invisible from the Stoofsteeg (point J & K) when there are more than 10 people walking in front of you. The only way to see the bridge deck and short end is from up close (1-2m).

The bridge is not visible at the cross section between Oude Doelenstraat and the Oudezijds Achterburgwal (point Q & R) due to obstruction by a flower store, but is fully visible from the intersection between the Molensteeg and the Oudezijds Achterburgwal (point B). This last point gives the best view over the Red light district side of the bridge as you are standing perpendicular to the side facing it straight. This is however at a distance of 180 meters.

Light and colour

The most prominent colours on the Achterburgwal:

1. Red - windows and (neon) signs.
2. Green - (neon) signs.
3. Warm white (<3000K) - street lighting.

Other aspects

Next to visibility, the parts of the bridge were also rated on three following aspects to determine the best spot for this lighting infrastructure.

Structural integration

It is important for a piece of media architecture to integrate the lighting with the structure it is placed on (Chapter: (E 2.3 | Media architecture)). The different lighting locations where each evaluated on the possibilities to follow and preferably enhance the shape of the bridge.

Figure E.15: *Left: Measuring method*

Shape freedom
Each lighting location was also rated on the possible shapes the lights self can diverge into. The handrail is for example a relatively 1D shape compared to the sides of the bridge which are strong 3D shapes with relief and thus gives considerably more options for different lighting techniques. This is important as the bridge is functioning as a showpiece and so should the lighting infrastructure.

Crowd blockage
This visibility test was done during relatively quite times during the day. However, in the evening hours and night, the Oudezijds Achterburgwal will be one of the busiest areas in Amsterdam (Figure E.14)(Figure E.16). For this reason, the different parts of the bridge were also rated on the amount of visibility blockage by pedestrians caused during busy times. This was done by looking at pictures of the different points of the bridge while it was crowded, and give an overall estimation of the blockage. Based on the mentioned criteria, the three best lighting locations were selected (Table 1.1).

Figure E.16: *The busy Oudezijds Achterburgwal.*

Visibility from different locations

	Location	Handrail (one side)	Inside (one side)	Outside (one side)	Underside	Deck	Opposite quayside		Overall visibility
Visibility % from point:	A	10	0	10	0	0	60		13,3
	B	100	0	100	0	0	100		50,0
	C	0	0	0	0	0	60		10,0
	D	50	0	50	0	0	80		30,0
	E	50	0	50	0	0	80		30,0
	F	0	0	0	100	0	0		16,7
	G	100	100	0	0	100	0		50,0
	H	75	0	75	0	0	100		41,7
	I	100	0	100	0	0	100		50,0
	J	5	0	0	0	0	0		0,8
	K	80	80	0	0	80	5		40,8
	L	95	0	95	0	0	50		40,0
	M	100	100	0	0	100	50		58,3
	N	100	100	0	0	100	20		53,3
	O	95	0	95	0	0	95		47,5
	P	100	0	100	0	0	95		49,2
	Q	50	0	50	0	0	95		32,5
	R	100	0	100	0	0	100		50,0
	Overall visibility %	67,2	21,1	45,8	5,6	21,1	60,6		36,9
Structural integration	- = -5	+	+	+	-	0	-		
Shape freedom	0 = 0	-	+	+	0	0	-		
Crowd blockage	+ = +5	+	-	+	+	-	+		
Total score		72,2	26,1	60,8	5,6	16,1	55,6		

Table 1.1: *Above: Detailed numbers on visibility of each part of the bridge from different measure points (stems of 5%)*

Figure E.17: *Right: Vector map of the Oudezijds Achterburgwal with trees and measuring points placed.*

Conclusion

Physical obstruction of vision on the bridge is caused by (in order of most to least obstructing): pedestrians (when crowded, mainly evening hours), trees, street lighting, parked cars, and bicycles. The most favourable spots to place the lighting infrastructure are (most to less preferred): the handrails, the two outer sides of the bridge, and the opposite quaysides. A combination between two or more spots is possible provided that the whole still appears as an integrated solution.

Handrails

Placing the lighting infrastructure on the handrails (Figure E.18) will make it visible for both the people standing on the bridge and the people standing on the quayside/street at different locations. Following and emphasising the simple shape of the handrail will increase the structural integration, but this simplicity also means there is less freedom in light shape.

Outsides

Both outer sides of the bridge are visible from the street and quaysides left and right. They also form the biggest surface for possible light placement, and the most shape freedom. The red light district side of the bridge (Figure E.19) is most crowded and can catch a lot of attention.

Opposite quayside

The last of the three spots are the quaysides (Figure E.20), of which both are visible for people on the bridge, and one is visible for people on the opposite side of the water or quayside. As the quayside is a flat wall sticking out of the water, there is not much room for wild shapes. Structural integration with the bridge can quickly be lost if there is no clear connection between the two made by the lighting infrastructure. This spot has the benefit of stretching for a long length and could be visible for a lot of people for a longer period of time.

As of yet it is unknown how the bridge looks like when light is projected on its surface, the following chapter will discuss this topic.

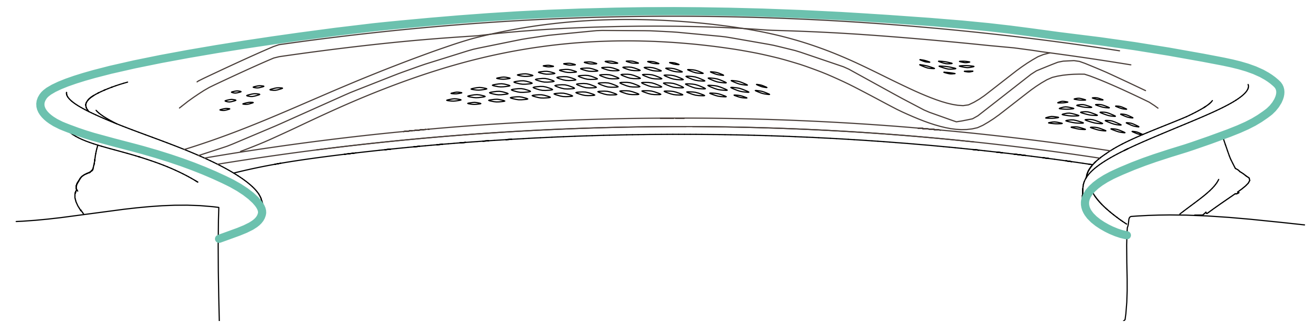


Figure E.18: *Handrail*

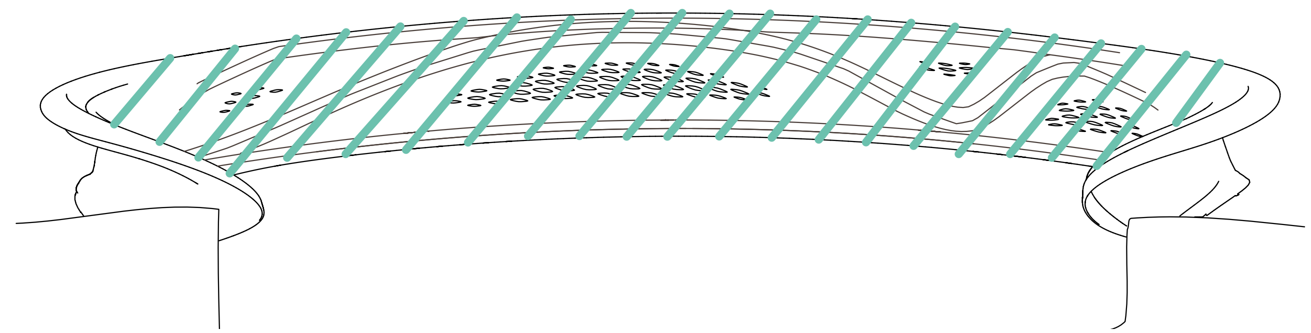


Figure E.19: *Outside*

Figure E.20: *Opposite quayside*

E 2.6 | Bridge light properties - light reflection

To see how light behaves on the 3D printed material of the MX3D bridge, a test on light reflectance was conducted. With this test it is possible to determine if indirect lighting of the bridge is possible, if reflective coatings are needed (Moynihan, 2015), or only direct lighting is suitable (Figure E.22).

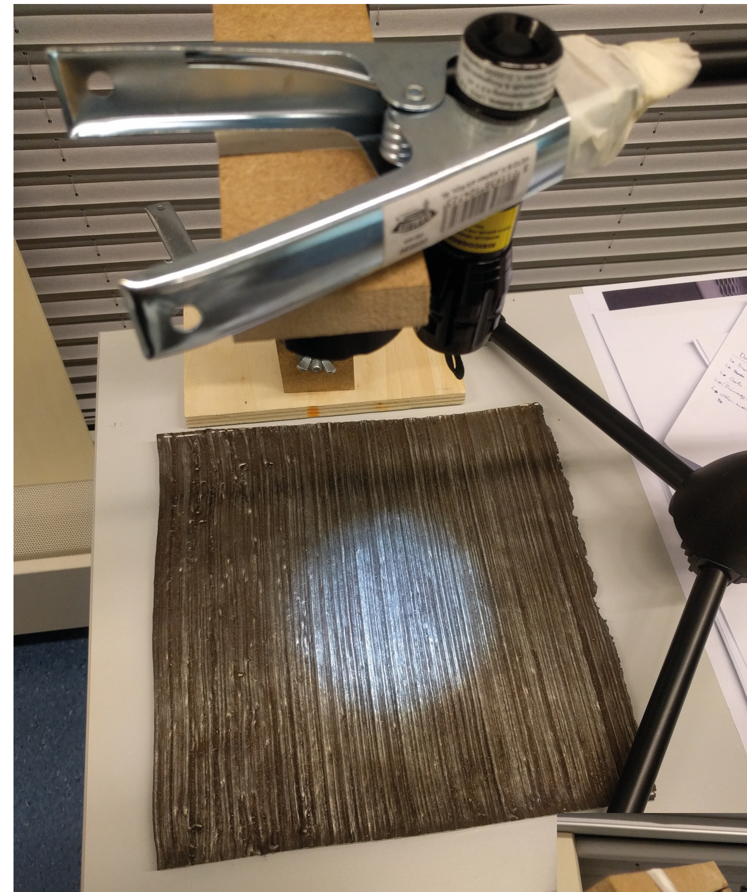
> ? *Is it possible to use the bridge as projection canvas?*

Approach

A lux sensor was placed on a swivelling arm with a height of 30 cm, and a 3W battery powered LED light was mounted on a static tripod in such a way that it was lighting up the centre of the sample (Figure E.21). Each measurement was conducted twice in whole sets, at the angles 0° (lux sensor perpendicular to the sample), 18°, 36°, 54°, 72°, and 90° (parallel to the sample). A piece of white A3 sized printer paper was used as a reference for maximum reflectance (on a matt white body), and ambient light offset (LED light source was off), while a black piece of A3 sized paper (darkest material available during the test) served as minimum reflectance. The bridge sample was measured in two directions to find out if there is a noticeable difference between the print directions.

Analysis

Appendix@@@ shows the detailed results of the test. The two measurements of each sample are averaged and compared to the reference measurement. Figure E.23 shows the percentage of reflected light in comparison to the white reference measurement.
The difference between the measurement at 0° between the two bridge samples seems to be a measurement error (there should be no difference). The fact that the two averages are diverging gives the impression the longitudinal printing direction reflects slightly less than the latitudinal direction.
According to Koerner (2018) an average light intensity of maximum 100 (day) to 50 lux (floor must be brightest) is needed on the MX3D bridge. As on average 30% of the light is reflected by the bridge (appendix: (A | Light reflectance test results)), the light intensity shining on the bridge should be at least 30% higher (130 to 65 lux on average). With current LED technologies this is certainly possible. For example a CFT-90-W led from Luminus outputs 5500 lumen maximum, over a surface of 10 square meters this is the same as 550 lux (Luminus Devices, 2017).



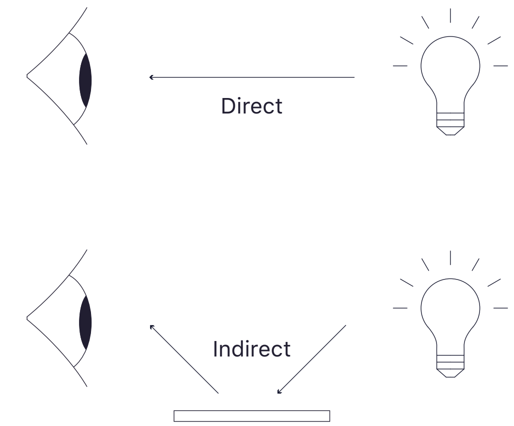


Figure E.22: *Direct and indirect lighting.*

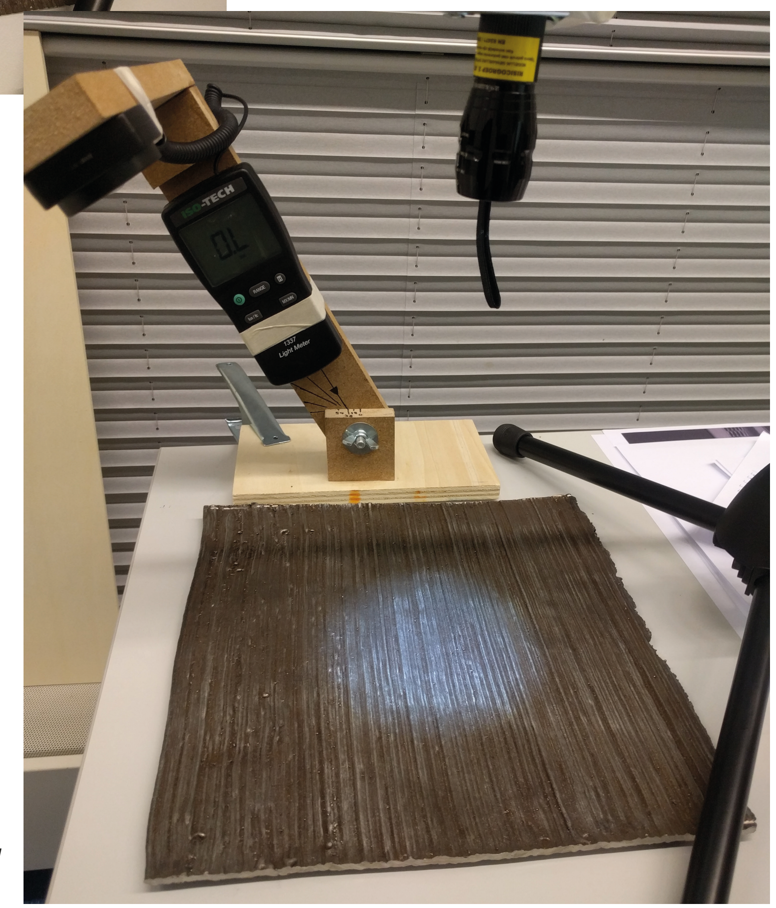


Figure E.21: *Top: The test setup at an angle of 0° . Bottom: The test setup at an angle of 36°. Note: the photo was taken with the ceiling lights on.*

Conclusion

It is possible to use the MX3D bridge as canvas and project light onto its surface. It will reflect enough light without additional reflective coatings or treatment of the raw material, however the angle of reflection influences the amount of light reflected. The average light intensity emitted should be 100 to 50 lux depending on distance from the floor (floor is brightest).
This test has been conducted with cold white light, it is expected that certain colours will be absorbed more than others (the bridge is not white). This can be validated with a spectrometer in the visual domain, however this is optimisation and only relevant for colour calibration.

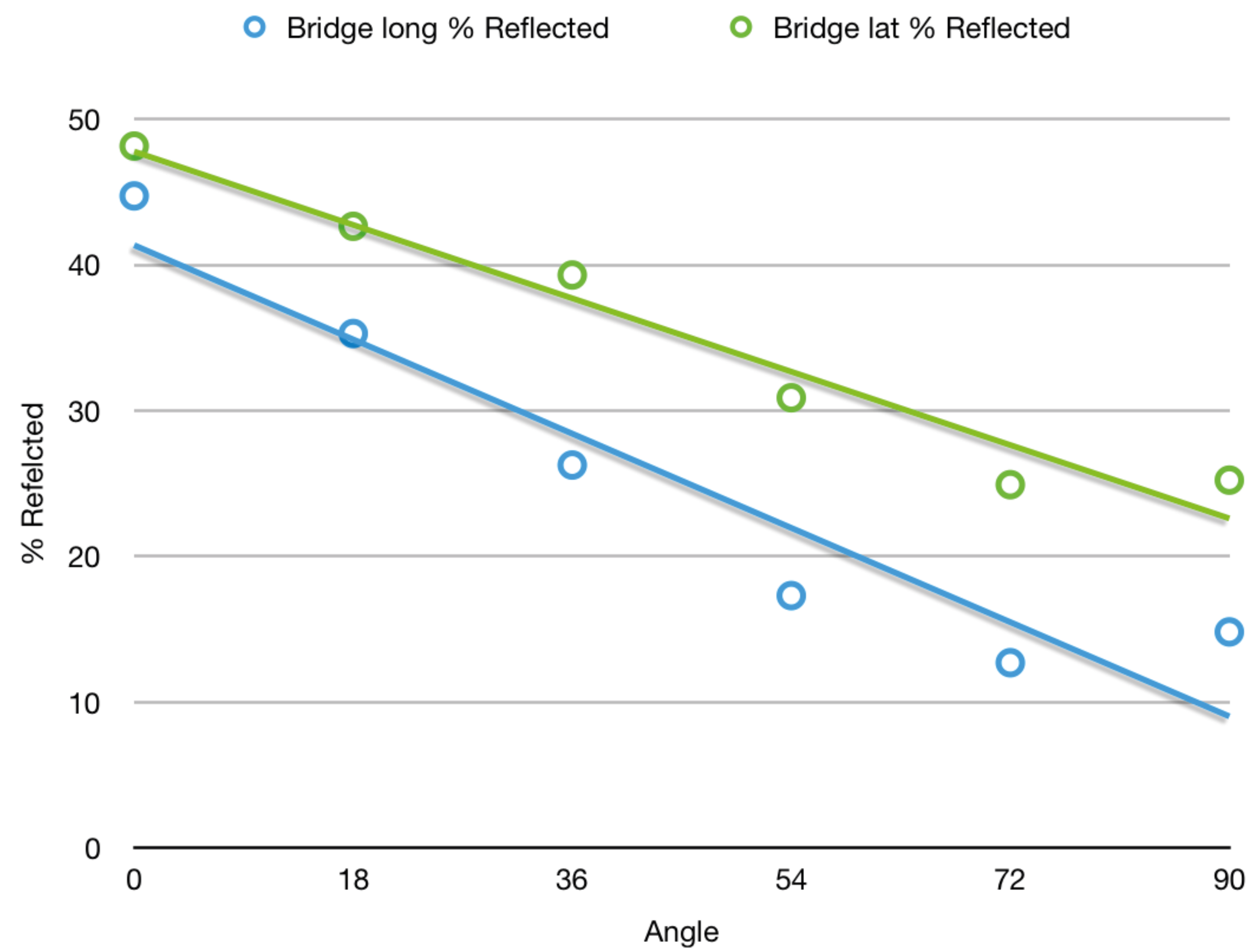


Figure E.23: *percentage of reflected light per sample at a specific angle.*

E 2.7 | Summary

The discussed topics in this chapter resulted in valuable insights on the usage of light on the MX3D bridge, design constrains and topics for further exploration. The next chapter will discuss the data that will be used to control the lighting infrastructure and creates opportunities to use this data.

Design insights

Basics of light

- *Using focal glow and play of brilliance seems most interesting to display data due to their ability to show/highlight detail.*
- *Ambient luminescence is already present on the bridge in the form of street lighting, signs, and other wide emitting lighting.*

Lighting in architecture

- *Light will be used to transfer information (functional lighting).*
- *Essential lighting (for safety) is not needed on the MX3D bridge as the current bridge does not need it either due to enough lighting in the area.*

Media architecture

- *Physical integration of carrier and messenger is required.*
- *Content should have social impact in its environment.*
- *Content should be easy to understand.*
- *ViP method should be used to create a valuable purpose.*

Animations

- *Animation should be understandable with a quick glance.*
- *Interpretation and correct understanding of an (aesthetically pleasing) animation by the audience is necessary, and should be evaluated.*
- *The lighting infrastructure should be pixel based for up close interactions, and ambient light based for longer distances.*
- *The animation is a portal to data from the bridge, and should enrich the environment.*

Visibility of light on the bridge

- *Handrail is overall the most visible spot on the bridge from all perspectives.*

Bridge light properties

- *Emitted light intensity by the bridge should be 100 to 50 lux on average.*
- *Direct and indirect lighting is possible on the bare surface of the MX3D bridge.*

E3 | Understanding data

This chapter will discuss the smart bridge project in general, the available data and sensors, and will conclude with insights on what data is available to control the lighting infrastructure.

To measure the structural integrity of the bridge while in use and gather data to specify the 3D printed material properties, the Smart bridge project team* designed a sensor infrastructure that will be installed on the MX3D bridge (Arup, 2018). On the second place the structural data will be analysed and used to gain contextual information from the bridge, what is happening on and around the bridge.
Starting with the basics of data analysis, followed up by analysing the source of the data and the sensor infrastructure, were after the system components are step by step analysed till the final data output, will create a clear understanding of what data is going to be available. At the same time valuable insights in present and future available data, implementation obstacles, and a general understanding of the system will be formed.

- ? *What data from the bridge is useful to control the lighting infrastructure with?*
- ? *What data is available from the MX3D bridge?*
- ? *What are the obstacles in using data from the bridge?*

Figure E.24: *Data visualised on the MX3D bridge (impression) (MX3D, 2018).*

E 3.1 | Basics of data science

The MX3D bridge is said to be smart, however what does smart in this context actually mean? To find out where this smartness comes from and what it can be used for, a basic understanding of data analysis is needed.

? *Where does the MX3D bridge its smartness comes from?*

Data science, artificial intelligence & machine learning

The sensors on the bridge produce data, but this data just represents some arbitrary values, and no real knowledge or insights. This is were data science comes in which is the study of extracting knowledge from data. It uses i.e.: prediction, statistics, artificial intelligence, machine learning, and optimisation to do so (Dhar, 2013).
It is already known that Autodesk will use machine learning to extract contextual data from the bridge. How does that work? Machine Learning (ML) is a subset of Artificial Intelligence (AI) and enables computers (machines) to train, learn, and progressively improves performance on a specific task by using data and experiences, augmenting human capabilities, increasing speed and efficiency (Microsoft, 2018) (Kunal, 2015). Artificial Intelligence refers to programming a computer so that it can take rational/intelligent decisions (from a human perspective) by perceiving its surroundings and trying to maximise its chances to achieve its goal (Poole, Mackworth, & Goebel, 1998).
For this project, ML is used to recognise patterns and events that are very hard, if not impossible to detect when using manual data analysis methods. This is due to the fast amount of real time data that needs to be processed. Another advantage of ML is the option to progressively improve accuracy, and find new insights over time.
Figure E.25 shows a very simple representation of a basic ML cycle. There are many different types of machine learning cycles, each with its own goal to classify, cluster, estimate, or otherwise learn from the input they are given (Karl Seiler, 2016). Autodesk uses a camera tracking system to create known data (what is really happening on the bridge), validate the ML algorithm, and letting it learn.

Internet of Things

"Connected does not mean smart" (Wal, 2018). The core idea behind internet of things is that a big amount of sensors can extract more information than just the sum of sensors, all sensors together form one new sensor sensing the overall context. This is also the case with the smart bridge, where the set of different sensors make the bridge itself a sensor for its surroundings (Meta sensor) (Tessier, 2018). This sensor bridge will then be a sensor for the city.

Conclusion

The smartness of the MX3D bridge comes from the analysis of the realtime raw data by the Autodesk ML algorithms, especially learning the bridge what is happening around it creates this extra level of insights unseen in other architecture. The bridge is not only a connected sensor, but has "knowledge" of its surroundings creating contextual awareness.

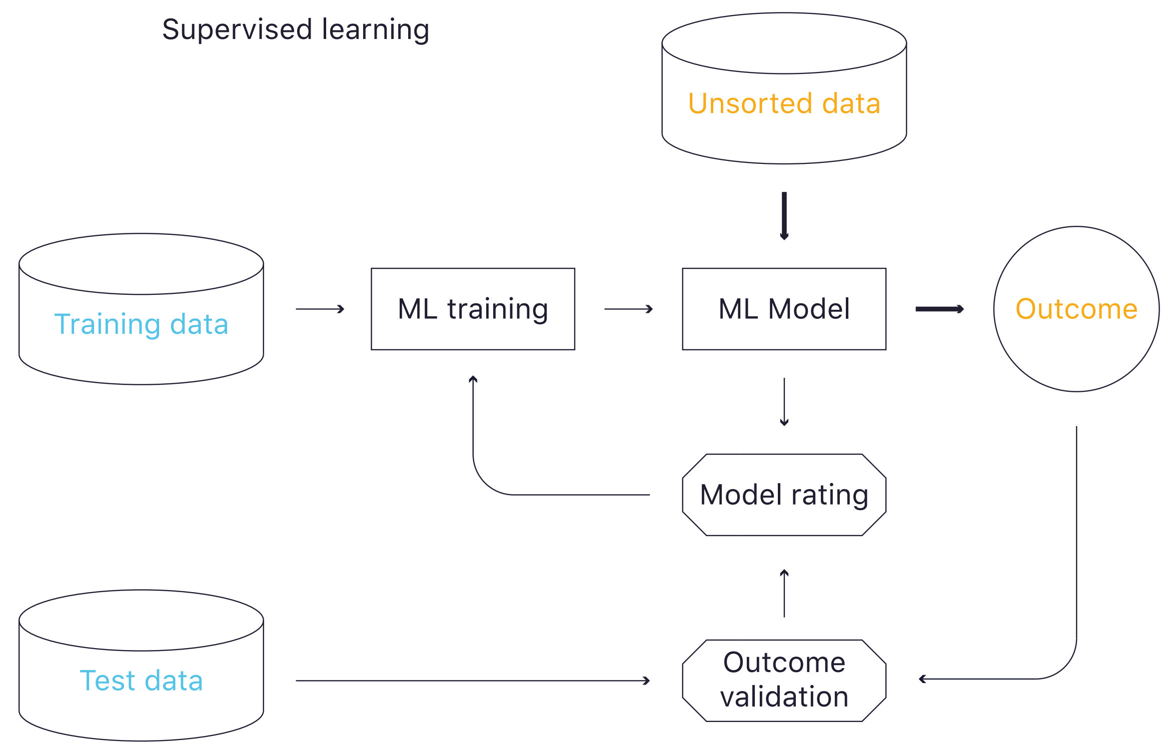


Figure E.25: *In this ML cycle, training data is used to find a working algorithm. The outcome of the analysed data by this algorithm is tested against known data, and based on the score of these test, the algorithm is rated. The outcome of this process is an optimised algorithm with the most accurate predictions.*

E 3.2 | From sensor to data - The sensor network

To gain a better understanding of the data generated by the bridge and find proper uses for it, a study on the sensor infrastructure itself and how it came to be was done. First, different information channels (Slack, Shared files, project logs) from the Smart bridge group were evaluated, to gather insights on the available sensors, their placement, uses, and data. Secondly, a semi structured interview with Autodesk provided information about physical challenges and limiting factors of the sensor infrastructure.

? *How & what data is being harvested?*

? *What are limiting factors in the sensor infrastructure?*

Data flow

Reviewing recorded meetings and meeting notes from the Smart bridge project team (Slack, 2018), and attending one of the meetings in the MX3D office (MX3D, 2018) formed a overview of what the sensor infrastructure will look like, and with what use in mind specific sensors were chosen (either: structural analysis, contextual analysis, or both (appendix: (B | Data flow diagram)).

As this is a sensor infrastructure, consisting out of multiple different sensors, communication from the sensors to a central spot is a key element. Figure E.26 is a schematic representation the sensor infrastructure, placement in the whole bridge system, and flow of the data on the bridge based on the different information sources.

he sensors on the bridge are connected to different sensor hubs that convert the analog sensor signals to digital signals (ADC, analog to digital converter)(DDC, digital to digital converter) and do some pre processing of the data. This data is then transferred over CAN-bus to the main sensor hub, or directly connected to the bridge server by ethernet.

From analysing the figure, it was concluded that both sensor and light infrastructure follow in principle the same hierarchy, and thus the same limiting factors apply.

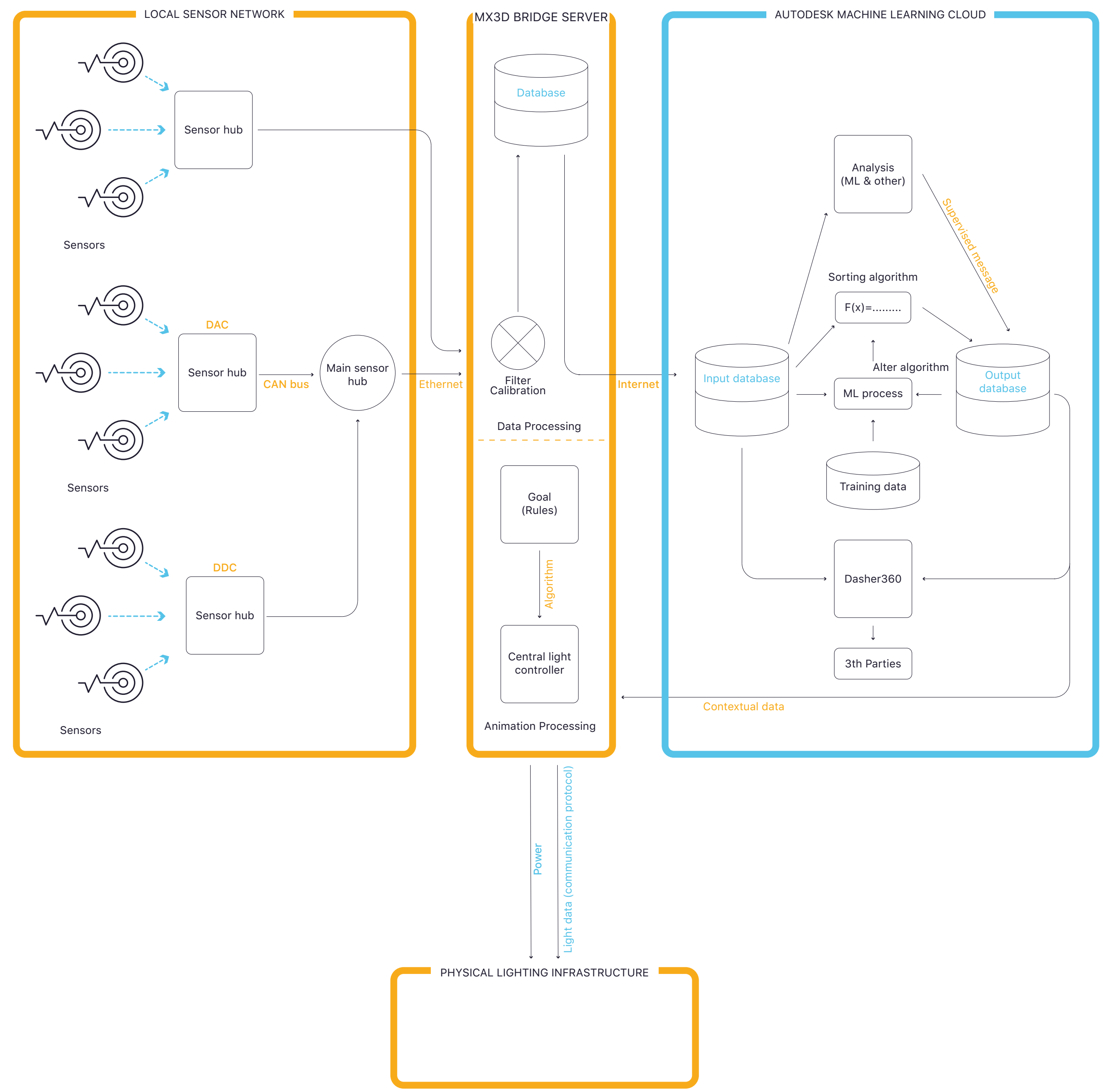
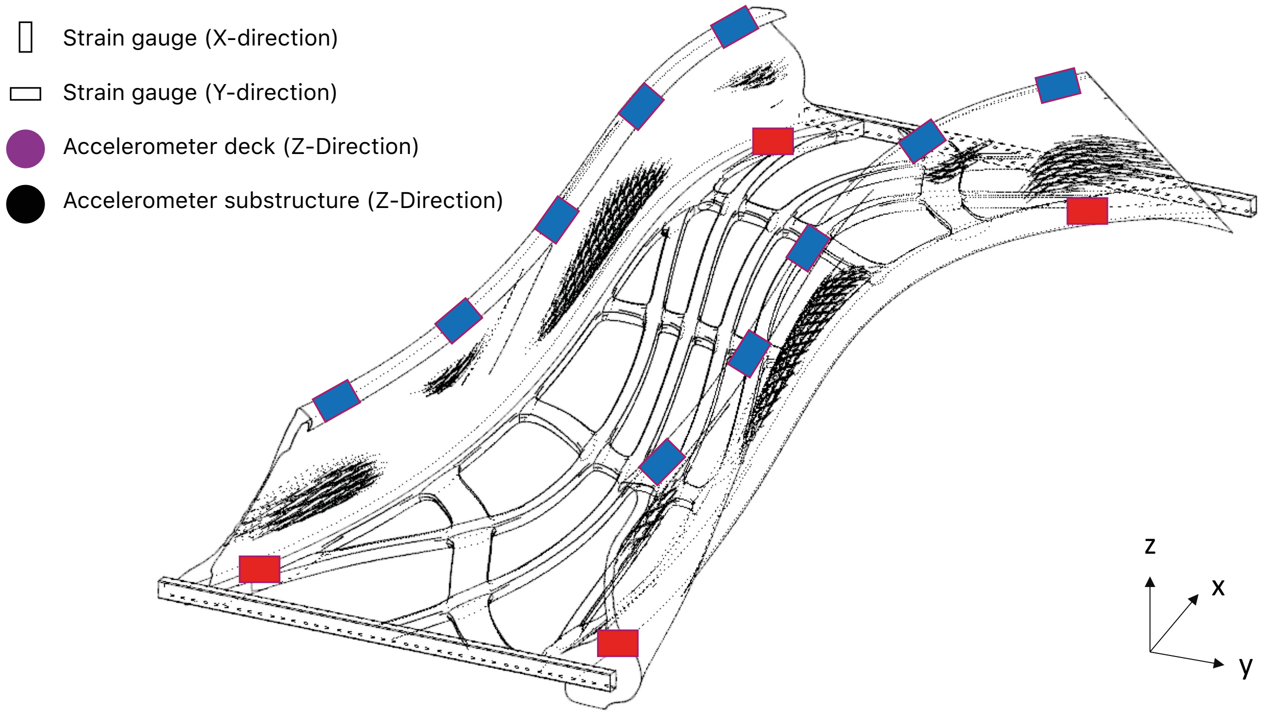


Figure E.26: *A similar tree type hierarchy could be applied to the lighting infrastructure, where instead of sensors there are lights, and the data is flowing in the opposite direction.*



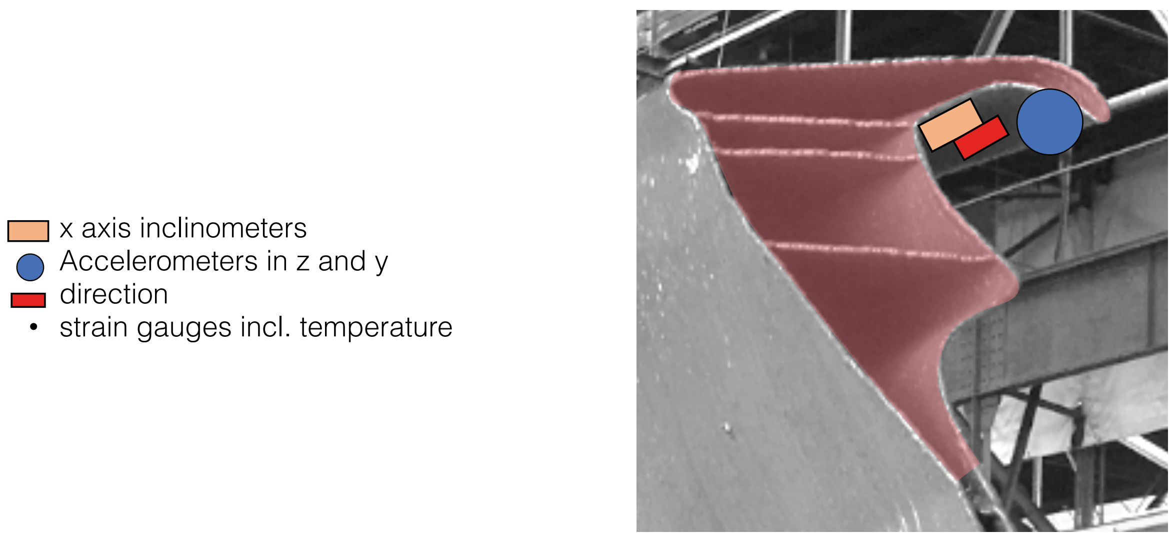


Figure E.27: *Sensors in the hand rail.*

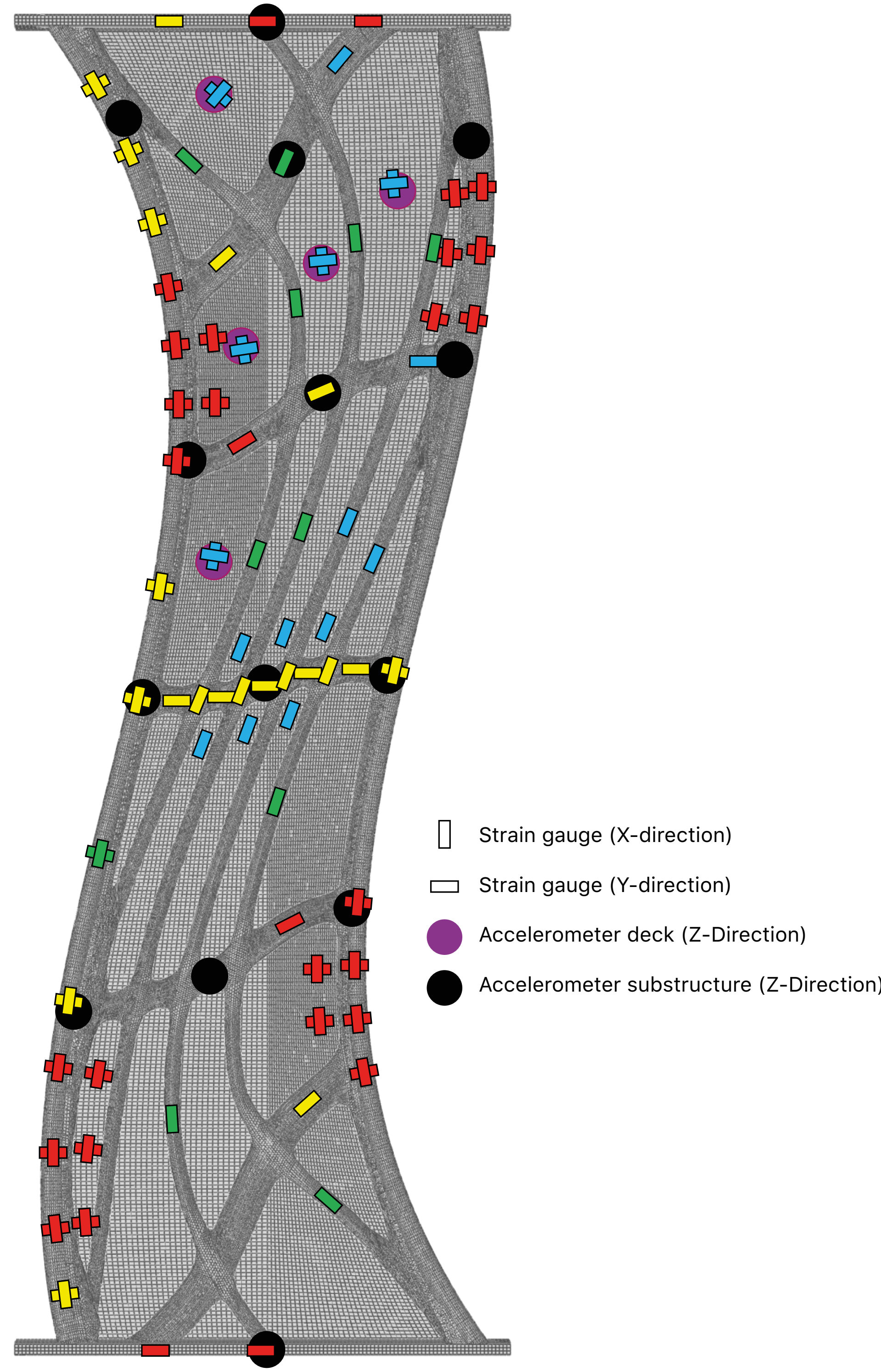


Figure E.28: *Top view of the bridge; Sensor placement for the substructure and deck of the MX3D bridfe (Arup, 2018).*

Sensor types

The MX3D bridge will have the following main sensors (Figure E.29) installed for gathering data. These sensors produce the bulk part of the data:

Accelerometer:

This is a digital sensor (MEMS chip) that outputs an acceleration value (m/s^2) in 1 to 3 axis. This sensor will measure vibrations on the bridge.

Strain gauge:

This sensor measures the strain at a specific point and after i.a. temperature calibration outputs a strain value (ε). Strain is a value for displacement of molecules, which means you can see how the point the sensor is installed at deforms.

Load cells:

A load cell is the sensor that measures the weight in your digital kitchen scale. It is in fact a set of four calibrated strain gauges. The combination of four load cells makes it possible to measure the weight of the whole bridge and everything on it.

Figure E.27 & Figure E.28 show the placement of the different sensors on the MX3D bridge. These placement went trough various iterations to find the most feasible, and most useful spots for the sensors.

The increased density of the number of sensors in the handrail and deck, results in a bigger amount of data in these areas. The placement of the strain gauges follow the shape of the structure to get the most accurate structural data. Other sensors are also installed on the MX3D bridge and can be found in appendix: (C | Sensor list).

Conclusion

Understanding the placement of the sensors created an understanding in what data they could generate, narrowing down the search for useable data from the bridge for the next chapter. Analysing the structure of the sensor network created insights in how the lighting infrastructure could be designs, only with a data flow in the other direction (Figure E.26). The localised placement of the sensors means the highest data accuracy is in those areas, which means other areas are less accurate or not measurable. Using mainly three types of sensors could result in missing data or accuracy. However this may be fixed by the machine learning algorithms if they can indirectly recognise events that are normally directly measured by other type of sensors.

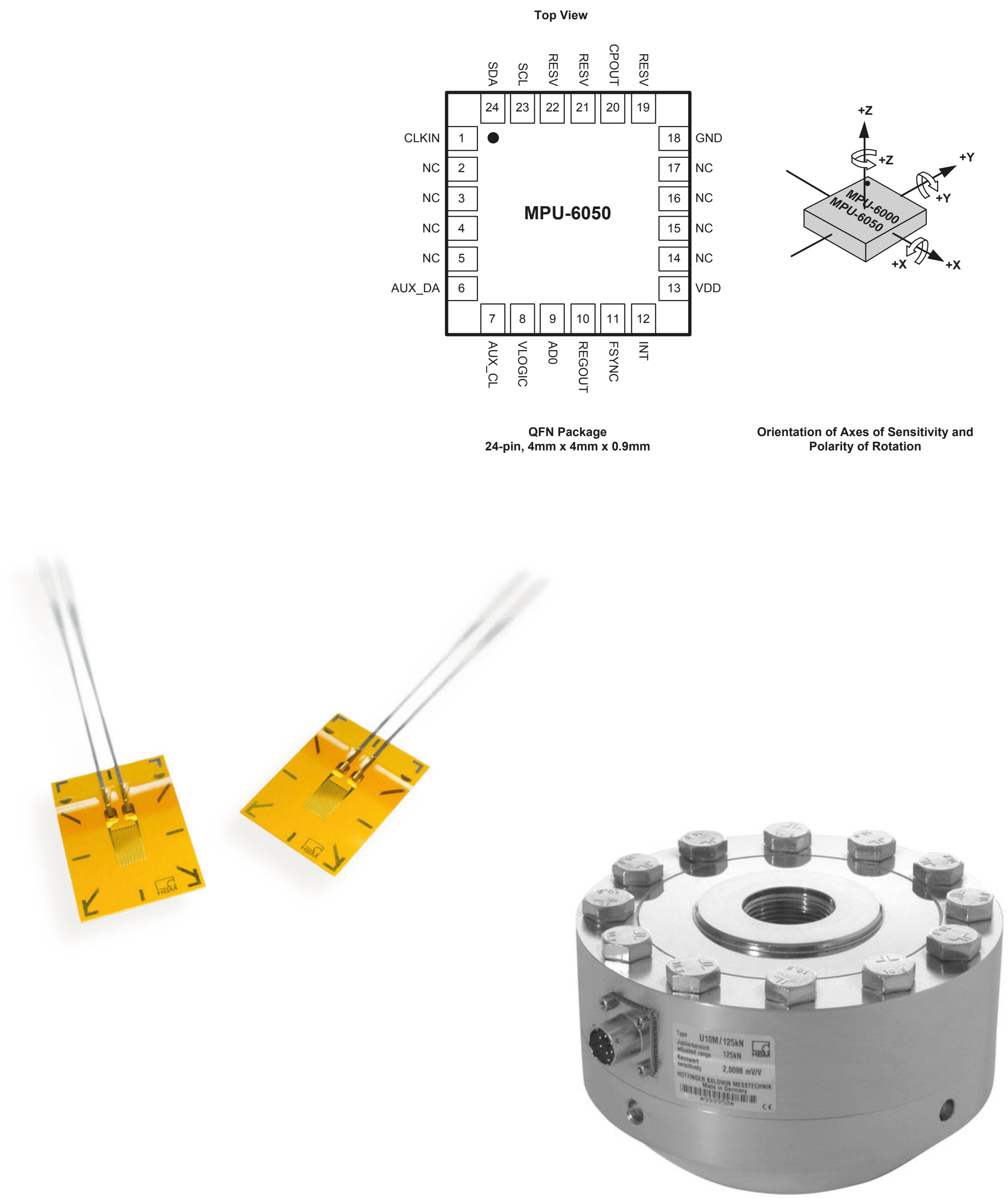


Figure E.29: *Top to bottom: Accellerometer/Gyroscope chip (InvenSense), Strain gauges (HBM), Big Load cell (HBM).*

E 3.3 | Example case - Implementation

Now that the source, flow, and analysis of the data is know, some questions arise on implementation of this data. An interview with Autodesk and an analysis of their existing prototype smart bridge will shine a light on the physical aspects of acquiring and using this data.

? *Is privacy taken into account in the smart bridge project?*
? *What insights did Autodesk get from their prototype smart bridge?*

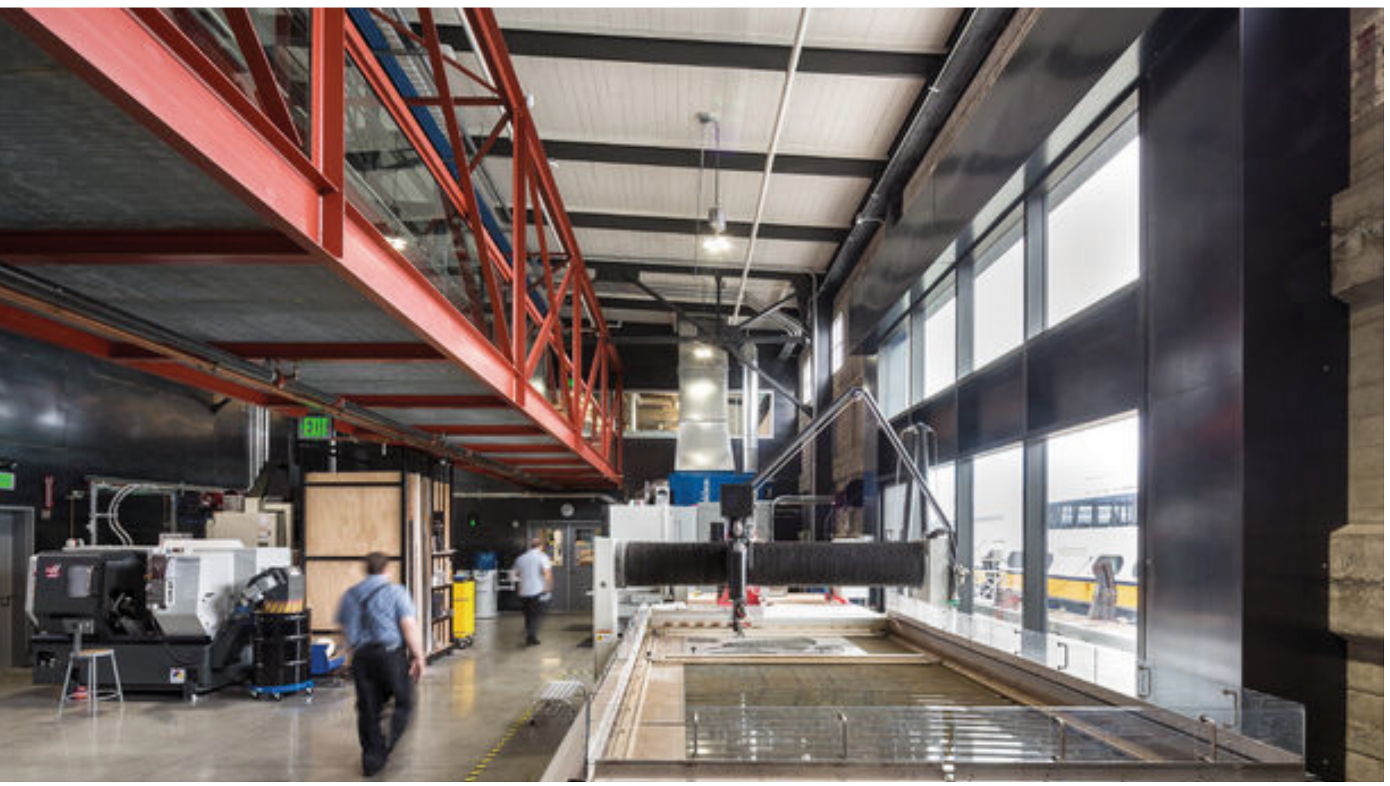


Figure E.30: *The Pier9 bridge in Autodesk's machine shop.*

Interview

A semi structured interview with Alec Shuldiner & Alex Tessier from Autodesk was conducted (appendix: (D | Autodesk interview)) in order to get a better understanding of the role of machine learning in this project, the possibilities of their current sensor infrastructure setup and that of the MX3D bridge, privacy, and create a data model*.

Pier 9

Autodesk is currently testing a simplified version of the sensor network that will be installed on the MX3D bridge on their own small pedestrian bridge crossing over the machine shop inside the Autodesk office in San Francisco called PIER 9 (Figure E.30)(Figure E.31). In the semi structured interview, it came to light that installation and maintenance of the sensors on the Pier 9 bridge was a real problem. Not only were sensors removed by cleaners and other people, installing them on the right place also formed a challenge. The main issue was that the bridge was never designed to be equipped with sensors, and thus Autodesk had to improvise. 3D printing the bridge gives the opportunity to directly include e.g. installation holes, wire tubes, maintenance hatches, etc. This is however not done with the MX3D bridge.
The semi structured interview with Autodesk, gave the following insights on bridge specific and unspecific challenges:

Data

- *Nowadays it is difficult to predict what data is possible to get out of a sensor infrastructure (using ML), future prediction models will make this easier.*

Privacy

- *MX3D is owner of the data.*
- *Data will be available for 3th parties.*
- *The current ML algorithms cannot detect personally identifiable information (p.i.i.). It may be possible in the future but it is an unwanted feature.*

* A data model is a model that describes data and the relations between the data. It does however not describe how or in what order this data is processed (Wood, 2011).

Noise Challenges

- *Noise is a big problem, not only sensor noise, but also (ir)regular noise from external sources like trucks passing by, boats underneath the bridge, etc. The external regular noise sources could however over time be identified and form another source of information. For example: the cleaning truck is delayed today.*
- *RF (radio frequency) creates noise, especially mobile phones are expected to cause problems.*
- *Resolution after processing the raw data can be too low to be useful in some cases.*
- *Wireless is not an option, not reliable enough, especially in public environments due to interference from other systems and devices.*

Physical challenges

- *Placement of the sensors is not accurate, in order to improve, the generated data has to be corrected.*
- *Keeping the sensors working on the bridge due to (accidental) vandalism, environmental destruction, or technical issues.*
- *Wiring and wire routing is difficult in closed tight spaces like the MX3D bridge.*
- *Location and number of sensors has a big influence on the generated data.*

Next to the mentioned facts, the interview also gave insights into machine learning. The machine learning algorithms that are being developed for this project are in an early stage and only use data available from the Pier9 bridge. Applying ML on the MX3D smart bridge requires creating new algorithms by learning with the new data from the sensor network, validating this data, and above all giving the system time to learn. As a result, the data coming from the MX3D bridge will get more accurate over time, but may not be accurate enough for some patterns and events to be measured / recognised correctly in the beginning.

Conclusion

Installation of the sensor infrastructure is very challenging, mainly due to MX3D not taking the sensor network into account during production of the bridge. The sensor network will be placed on the bridge instead of integrated into the bridge as would be possible with the 3D printing technology. This problem will also be true for the lighting infrastructure, as it consists mainly out of the same basic components.

Noise from the sensors and surroundings can cause erroneous or low resolution data, and will limit the usability of these sensors.

Figure E.31: *Side view of the Pier9 bridge (Autodesk, n.d.).*

E 3.4 | Data exploration - What can it be used for?

An explorative session was done to get a better understanding, find possible uses for the available raw data, and make a division based on data type and main use. Furthermore, an in-depth look into Dasher360 made clear what the digital twin of the MX3D bridge will look like, and how the data will be presented in a visual way.

- ? *What patterns can be extracted from the raw data?*
- ? *What will the digital twin look like?*
- ? *How will the data be visualised (after analysis)?*

Brainstorm

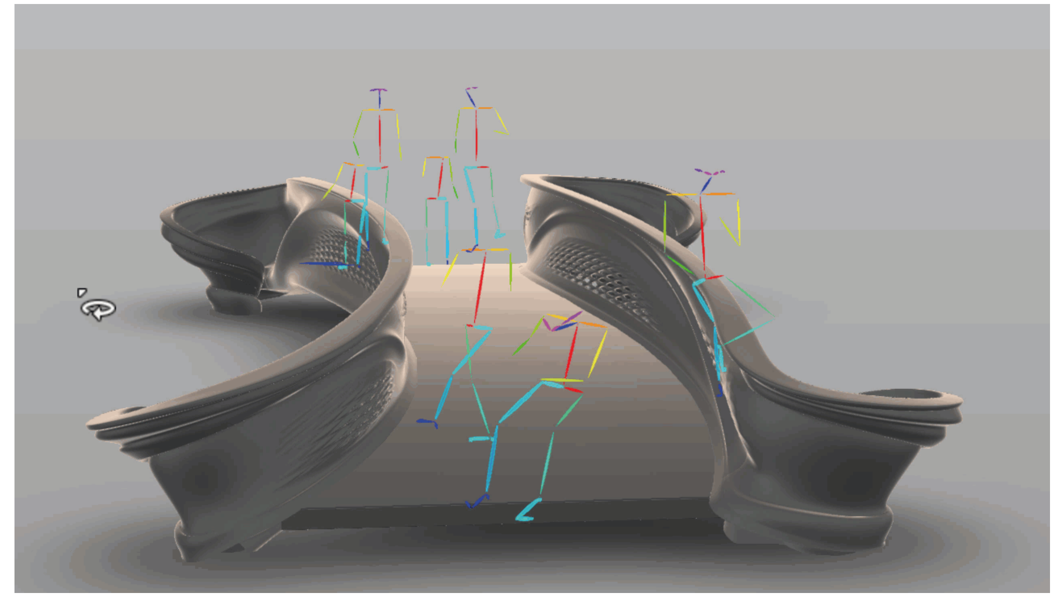
The patterns and divisions were created by brainstorming in a group of 5 IDE master students who were first made familiar with the context of this project. During the brainstorm, the participants were given a brief explanation of the project, the sensors, and the goal of this brainstorm. The following statement was being answered by the participants: Find patterns and uses based on the raw data coming from the sensors and categorise that data.

Digital twin

The digital twin will be visually presented in the cloud program Dasher360 (not yet publicly available) (Tessier, 2018). In this program a 3D representation of the MX3D bridge can be explored, and raw and analysed data can be explored. A proof of concept of the Pier9 bridge has been made available for this project (Figure E.33), and a basic version of the MX3D bridge digital twin was used at the Dutch Design Week 2018 in Eindhoven (Figure E.32).

Conclusion

The patterns people suggested (Appendix B) were mostly straight forward and only represent a small selection of possible patterns. However, some sensors were found to not be useable for generating contextual data as they are only useable for calibration, or are only sensing one value.
The visualisations in Dasher360 from both the MX3D and Pier9 bridge showed the raw data is detailed enough to recognise certain events (by humans) without additional processing.



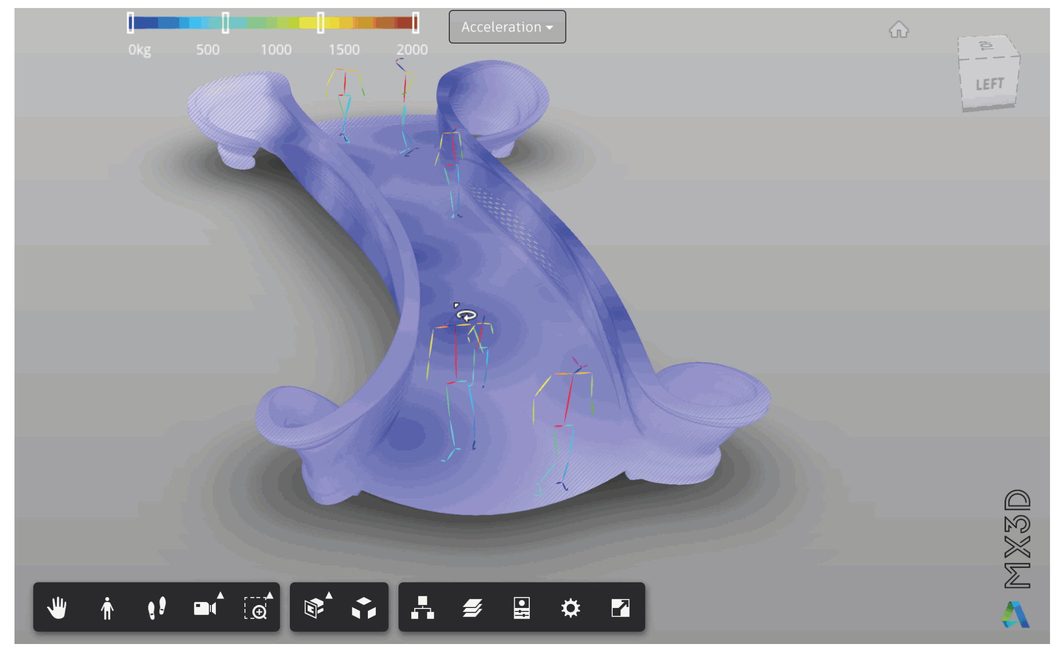
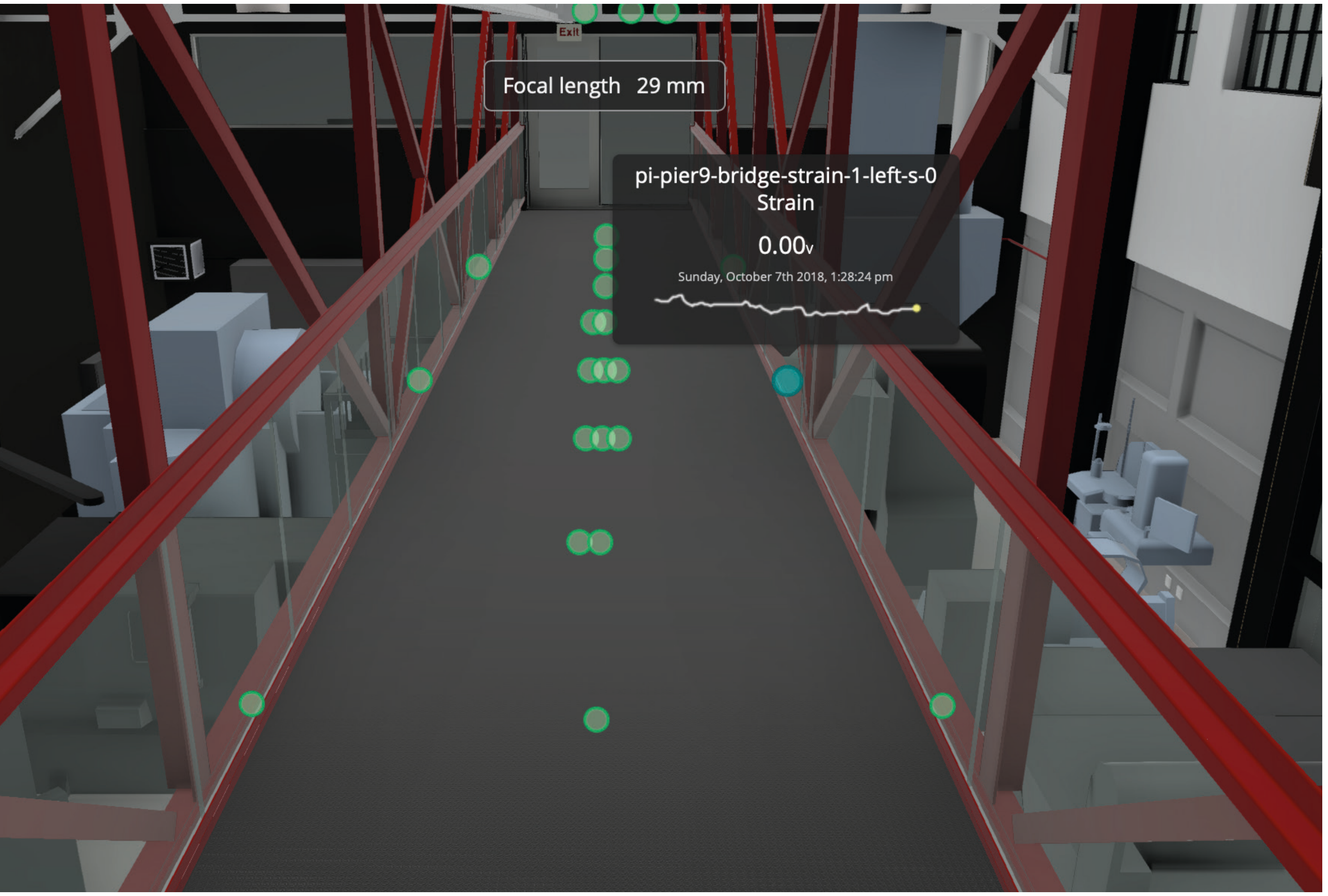


Figure E.32: *Top: Posture of people on the bridge. Bottom: Heatmap on the MX3D bridge.*



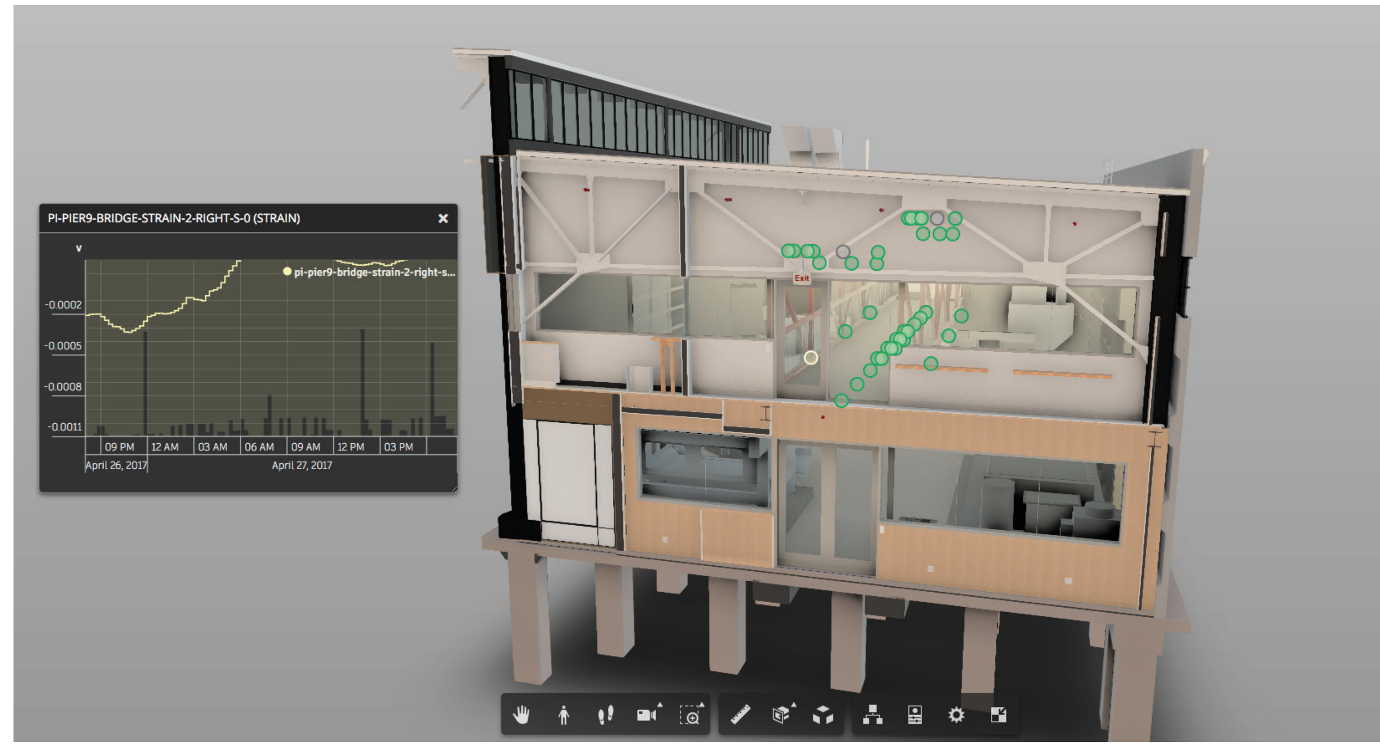


Figure E.33: *Left: The Pier9 bridge in Dasher360. Right: Pier9 bridge in Dasher360 with sensor data.*

E 3.5 | Data model - A list

Now that there is enough knowledge on the available data, it can be collected, categorised, and combined into a clear overview. This overview is called a data model.

Combining

Patterns, events, and data from the brainstorm session (appendix: (G | Data model)), the Autodesk interview, and the Pier9 example were combined into a data model* (appendix: (G | Data model)), and the sub set of data they consist out of was defined. This derived data is the actual data that can be measured, and comes either directly from the sensors (raw data), or is analysed first (by ML, or other algorithms).
The data model has been iteratively discussed with Autodesk, and validated for viability, current integration in the Pier9 bridge system, and future integration on the MX3D bridge.
In section one of the table the data is divided into the different levels of derived data. Section two of the table implements the insights and information coming from the interview, conversation with Autodesk, and data exploration, and shows the viability of the data points. The last section discusses why not all data points in the model are available or are expected to be available from the MX3D sensor infrastructure, and how alternative solutions can be found based on using or combining other sensor data, or enhancing the data analysis in the future.

Conclusion

The data model can be used as reference to find a valuable but also feasible purpose for the lighting infrastructure, and will be used later in this report.

* A data model is a model that describes data and the relations between the data. It does however not describe how or in what order this data is processed (Wood, 2011).

Some of the data in the data model:

- *Number of people on the bridge (incl. avg. walking speed and walking direction)*
- *Number of people crossing the bridge per time period*
- *Avg. time spent on bridge*
- *Current activities (walking, standing still, leaning, jumping, ...)*
- *Where are most people standing on the bridge (currently and aggregated over time)?*
- *Where are people leaning on the handrail (currently and aggregated over time)?*
- *Current location, walking direction, walking speed and orientation of each individual*
- *Current activity (walking, standing still, leaning on handrail)?*

E 3.6 | Summary

Step by step following the path of the data, talking to experts, and looking at current experiments, lead to a data model were the available data is described, were it originates, and what route it took. Next to this data model, insights from a practical perspective were collected. The next chapter will discuss the technology needed to bring the light, data, and bridge together.

Design insights

Basics of data science

- *The MX3D bridge becomes smart due to real time analysis of the generated data, and learning what is happening around it.*

The sensor network

- *A tree type hierarchy could be used for the data flow in the lighting infrastructure.*
- *Deck and handrail have a high sensor/data density, thus give most useable data.*

Example case - Implementation

- *Installation of the lighting infrastructure should be made as easy (non intrusive) as possible.*
- *Communication to the lighting infrastructure should be noise proof.*

Data exploration

- *Data is available on posture, location, direction, number of people, walking direction, etc.*
- *Dasher360 visualises the data without useful purpose for the people walking on and around the bridge.*

E4 | Understanding the technology

This chapter will discuss the currently available lighting technologies for bridges, other architectural objects, consumers, and professionals. The lighting infrastructure will be dissected into the basic elements as shown in Figure E.34, analysed, and a choice will be made on what technologies fit the MX3D bridge best.

- ? *Are appropriate standard lighting solutions available for the MX3D bridge?*
- ? *What lighting technologies fit the MX3D bridge best?*
- ? *What does a lighting infrastructure consist out of?*
- ? *How are the lights controlled?*

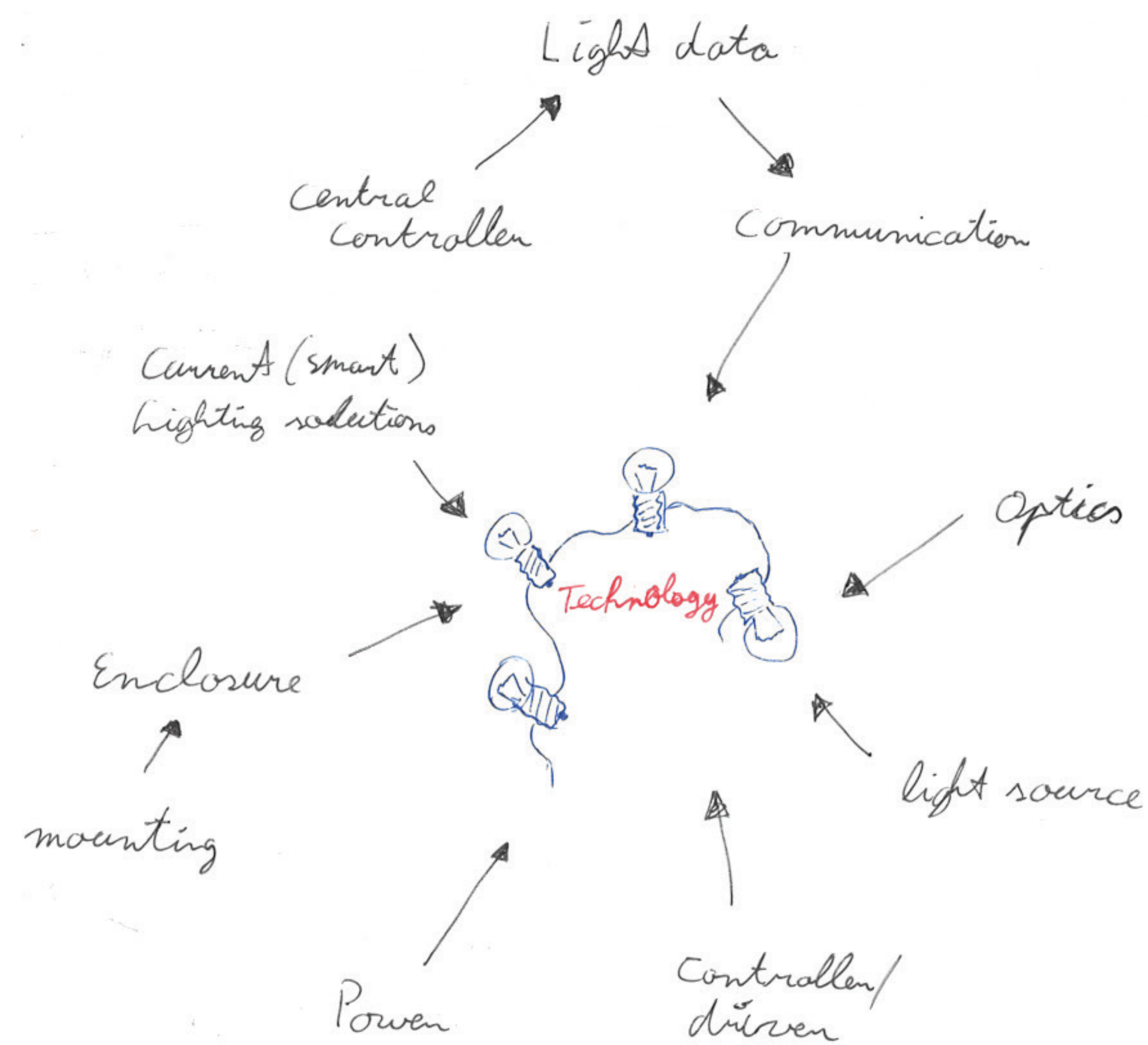


Figure E.34: *Elements of the MX3D lighting infrastructure.*

E 4.1 | Lighting infrastructure anatomy

A basic understanding of the anatomy of the lighting infrastructure is needed in order to make decisions on what technologies should be used. A separation is made between the light controller, and the light source (lamp) due to change in data.

? *How is the lighting infrastructure controlled?*
? *What parts does it consist out of?*

From data to light

The contextual data from Autodesk will be used to control the lights in the lighting infrastructure creating an animation. To do so in real time, the contextual data has to be converted by a lighting controller (Figure E.35), which can run on the central bridge computer or similar server. This lighting controller will get the contextual data from Autodesk as input, and filters out the wanted data, for example x-coordinates of the location where people are standing on the bridge. This input will then be converted to light data, e.g. what light, what intensity, what colour, at what time. The conversion happens with an algorithm/program (rules) which is derived from the intended purpose of the animation.

Figure E.35: *From contextual data to light data.*

Light source

There is a fast amount of different types of lighting sources available. appendix: (H | Light sources) represents a global overview with the main properties. To make a grounded choice on what types of light sources are appropriate for the MX3D lighting infrastructure, a deeper understanding on the parts of and around a light source is needed.

Source

Starting at the core of a light, the source of light. Most modern lighting uses LEDs as the light source, due to their high efficiency, low heat production, size, varieties in colour and shapes, ease of control, and price. Other types of light sources include indecent, noble gas, electroluminescent, and many other exotic types.

Optics

The optics of a light determine how the light beams will disperse from the light source. Optics could also include filters for different wavelengths or to create special patterns.

Driver / Controller

The driver is a piece of electronics that will control the power to the light source. The light controller is converting digital signals (e.g. Red = 100%) to signals for the driver.

Mounting & Enclosure

All parts are encapsulated into an enclosure, protecting the parts from erosion, vandalism, and create a mounting point for the whole light

Power / Cabling

Power and data distribution is often overlooked, however can cause major problems when neglected. Cabling takes up a lot of space, reducing this make installation easier and reduces costs. Especially on the MX3D bridge, space for cabling is almost non existing and must be taken into account.

Conclusion

A lighting infrastructure consists out of three main parts, the light controller, a communication and power network, and the light sources (Figure E.36). A central lighting controller has to be designed that converts contextual data to light data by using predefined rules based on the intended goal of the animation. This controller distributes the light data to the rest of lighting infrastructure via a physical wired or wireless network for power and data transfer, to the lighting fixtures or projectors. The topics that require further investigation are communication, and lighting technologies.

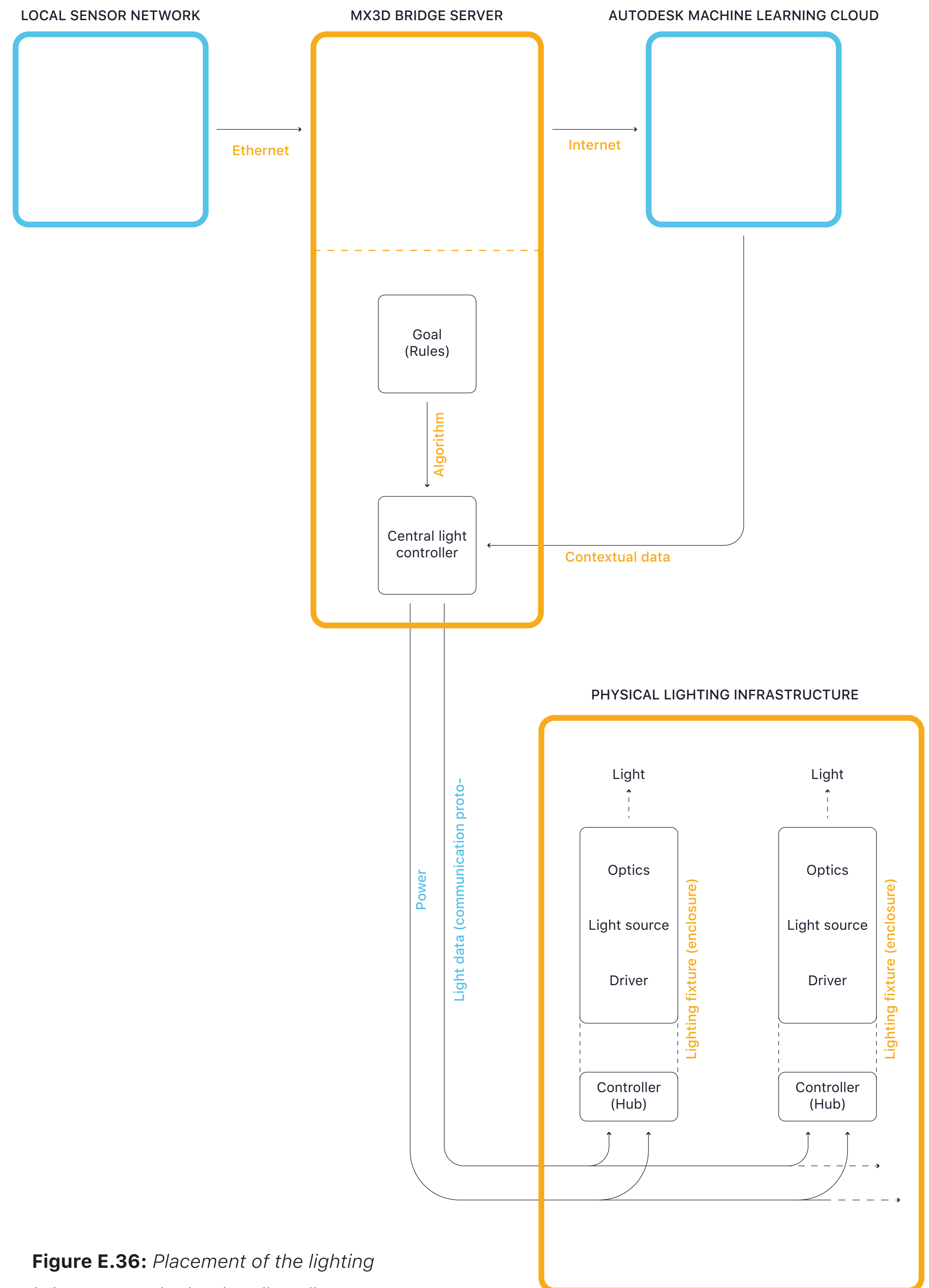


Figure E.36: *Placement of the lighting infrastructure in the data flow diagram.*

E 4.2 | Current lighting technologies

As smart lighting is a term well used by lighting companies (Inter IKEA Systems B.V., 2018), there may be an existing solution available for the MX3D bridge. An analysis on currently available technologies, products, and companies will clarify this question.

? *What smart, interactive, or connected lighting technologies and products are available on the market?*
? *Is one of the technologies or products a direct match for the MX3D bridge?*

Smart & not so smart lighting in architecture

The first question that arises is: what actually is smart lighting? Smart implies the possession of intelligence. But in consumer electronics, the term smart is often used for devices with remote controllability (e.g. remote thermostat control), or the ability to sense its environment and react to it in a simple manner (e.g. motion activated light) (Hollis, 2013). Smart lighting is based on this added functionality of remote or autonomous control using simple binary triggers or timers rather dan complex data analysis. Consumer lighting will become intelligent when it is controlled by a smart environment (domotics), this is an upcoming trend and not yet commonly used in every household (Gomez & Paradells, 2010).
Figure E.37 represents a selection of famous commercial enterprises delivering smart and not so smart lighting solutions for consumers and professionals. Consumer oriented lighting companies offer a great many types of remote controllable, interactive, interconnected (with other services), and colour changing lighting solutions (Figure E.38). The professional segment is more conservative and mainly offers lights that are controllable by a centralised lighting computer to regulate the lighting in big buildings (on/off, and sometimes dimming)(Figure E.39). The professional smart lighting is focused on putting the right amount of light at the right place and time, while consumer lighting has its focus also spread over mood and notification lighting.

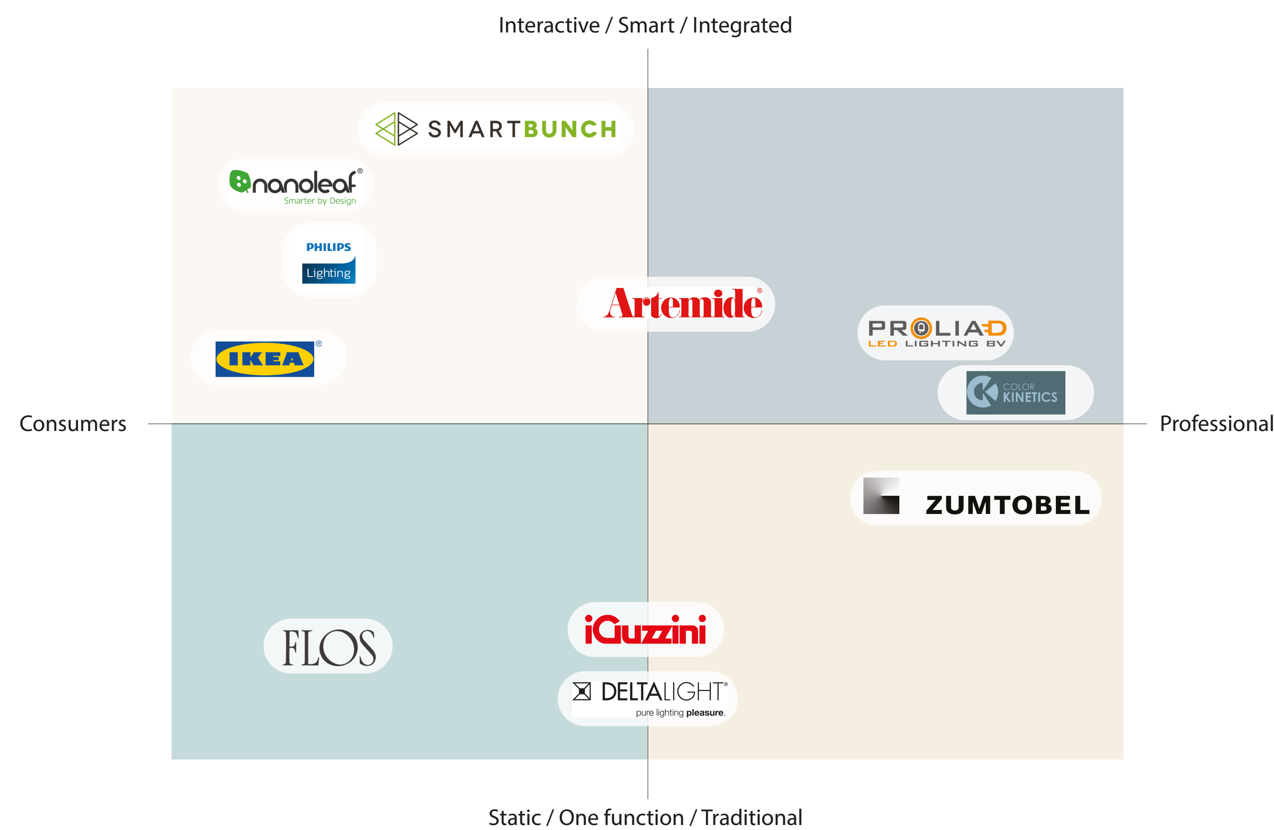


Figure E.37: *Smart lighting products.*

Figure E.38: *Top: Nanoleaf interactive consumer lights. Bottom: SmartBunch modular consumer light.*

Figure E.39: *Top: Colorkinetics outdoor light. Bottom: Zumtobel Supersystem II proffesional modular lighting.*

Figure E.40: *Projection mapping on the Philips building at the 2018 Glow festival in Eindhoven.*

Stage lighting

Stage lighting (Figure E.41) is another area were interconnected lighting infrastructures are used. This area is most interesting for its realtime fast responding and multichannel (thousands of channels) lighting. Standardisation means most lights can be directly connected to each other, making implementation easier. Stage lighting is very robust and in some cases even weather proof (IP65, IP66, IP67), making it suitable for outside use.

A sub type of stage lighting is the upcoming technique called projection mapping were a digital projector is used to project a video on a building or other structure. This technique takes into account the 3D shape of the structure by 3D scanning or manual adjustment (Figure E.40).

Figure E.41: *Moving head GOBO projector.*

Conclusion

Consumer lighting comes closest to combining data and light in a small and elegant form factor, but fails in transferring a clear message to the user which makes it art rather than an information display. On top of that, consumer grade lighting products don't scale well, are less rigid, and neglect the use of communication standards, and thus are unfit for use as a public lighting infrastructure.

Professional lighting lacks the compactness of consumer lighting, which makes it harder to integrate properly into a structure. Mostly multiple lighting and fixture standards are used in a product to ensure employability in different systems.

Stage lighting has a wide selection of different types of lights, while at the same time ensures inter compatibility by using standard communication.

As no lights were found that would solely work without either alterations to the bridge or lighting, custom lighting hardware has to be created to form an integrated solution on the MX3D bridge.

E 4.3 | Communication

The first step in the network will be communication to the lights. This chapter will discuss different technologies, methods, and principles, and defines what would be best for the MX3D lighting infrastructure.

? *What are the best communication technologies for the MX3D lighting infrastructure?*
? *Is it possible to use a standard communication method?*

Data origin

The first decision that needs to be made is where the light data (animation) is generated. This could either be on the light source itself (decentralised), or on a remote server (centralised). A decentralised solution is simpler to build, but has very little freedom to change any settings or animation patterns. This setup would have a preprogrammed animation in each light, and a central controller would only send an update signal, basic parameters, or animation select data.
A centralised solution where one host pushes all the light data at the right time to the correct light sources is more complex in communication, however it is very easy to change the animation (one place to change parameters). As stated in Chapter: (E 2.3 | Media architecture): the content should adapt over time based on the context. The best way to achieve this on the MX3D bridge is by using a centralised host controller that pushes animation frames to dumb slave nodes (lights), at a regular interval.

Wireless vs wired

Communication between the host and the light nodes can be achieved by using a physical (wire), or wireless connection (IR, RF). Wireless signals are very sensitive for interference, use more power, and are in general less reliable in comparison to wired signals (Tessier, 2018). As power requirements for the light sources require a wired connection anyway*, there is no added benefit to use a wireless connection on the MX3D bridge.

Serial vs parallel

Data can be sent to the light sources over wire in two ways, the data could be transmitted to all light sources at the same time individually (parallel), requiring a physical signal to every light source from the host. This is results in vast data transfer, but requires a lot of physical connections, and is sensitive for interference over longer distances (Mellon, 2016). The other option is to daisy chain all light sources together on the same signal (serial) which transfers a long string of data consisting out of consecutive parts of data addressed to each light source. This requires less physical connections, and is suited for long distances, however it requires more processing power to reach the same update speed as a parallel connection (Sebastian, 2017). On top of that, a serial connection is more scalable as only a connection between the previous and next light source has to be made.
As there is very little space for cable routing on and in the MX3D bridge, serial connections between the light nodes, controllers, and host are needed.

Synchronisation & Error handling

Synchronisation of the light sources is of great essence when making an animation. A mismatch in frame updates can cause glitches and other artefacts that distort the message that need to be transferred. The solution to this problem is to have a centralised clock signal that tells all light sources to update at the same time, or have software error handling (Stoffregen, 2018). This is easiest to achieve with a centralised controller.

Communication standards

With the above knowledge mentioned above and constrains on communication for the lighting infrastructure, it is possible to make a selection on the most suitable lighting communication standards for the MX3D bridge lighting infrastructure. appendix: (I | Lighting control protocols) represents a selection of commonly used lighting protocols and their properties.

Conclusion

A wired serial communication protocol is best suited for connecting all lighting infrastructure elements on the MX3D bridge for reliability, noice resistance, power requirements, and expandability. Art-net is the best lighting protocol for lighting fixtures as general infrastructure due to its high frame rates, many channels, and acceptance in the industry. As optional sub network (hub to driver), normal DMX can be used (appendix: (I | Lighting control protocols)). Projectors require a significant higher data speed and resolution and therefore best use a LAN connection to stream video from the central controller.

** One simple RGB LED without controller only lasts for maximum 47 hours on a good quality AA battery at 20 degrees Celsius ('ENERGIZER E91 Specifications', 2018): 2,85Ah(capacity) / 0,06A(LED) = 47,5h = 2 days.*

E 4.4 | Summary

Custom lighting hardware has to be created to form an integrated solution on the MX3D bridge that is both human, and weather proof. Using communication standards from the stage lighting industry, basic light sources from the professional architectural lighting industry, and the interactiveness of smart consumer lighting, ensures easy implementation and expandability, durability, and proper transfer of the animation.

A central lighting controller will convert the contextual data to light data and a physical wired network will distribute this data to the lighting fixtures by using ART-Net, DMX, or streaming over LAN while also take care of power.

Design insights

Lighting infrastructure anatomy

- *Smartness of the central light controller is in the conversion from sensor data to light patterns.*
- *A set of rules will translate the contextual data to light data.*

Current lighting technologies

- *Custom hardware solution is needed to create an integrated solution for the MX3D bridge.*
- *Either addressable LED strip, or projectors, assisted by soft spots can be used as light sources for the MX3D bridge.*

Communication

- *A central lighting controller will convert the contextual data to light data and distributes this data via ART-Net, DMX, or streaming over LAN while also taking care of power distribution for the lights.*

F Valuable purpose

As concluded in Chapter: (E 2.3 | Media architecture), the current lack of valuable purpose in media architecture asks to find and implement one for the MX3D bridge. The objective of this chapter is to find this valuable context based purpose for the lighting infrastructure, by creating a starting point to design an animation. The vision in product (ViP) method will be used to define a broad direction to go into, while an in field context observation will narrow down to a specific goal for the animation to fulfil.

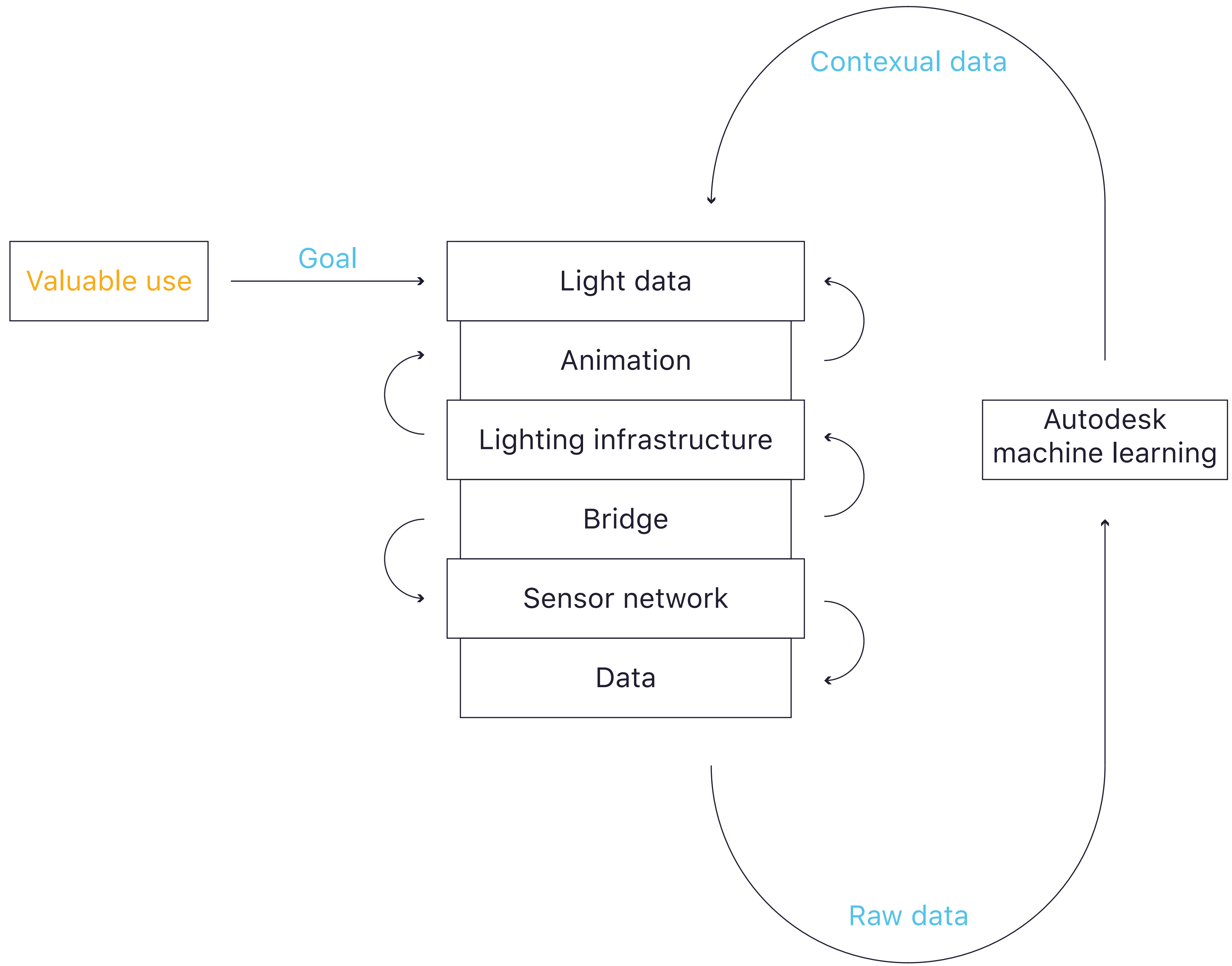


Figure F.1: *Where valuable use fits into the project.*

F1 | ViP

ViP, short for vision in product, is a context driven and interaction centred design method. Its main purpose is to help the designer develop the underlying purpose of a product, also called 'raison d'être' or the 'why', giving the product meaning or value, exactly what is needed for the lighting infrastructure (van Boeijen, Daalhuizen, Zijlstra, & van der Schoor, 2014). As the purpose of the ViP design method for this thesis is to find a valuable purpose only, a simplified implementation is used. The preceding chapters were analysed not only on technical level, but also on context, function, and what they express. The insights gathered there, in combination with a trend analysis on the topics smart cities, IoT, architecture, and social behaviour in the city, resulted in the ViP statement (appendix: (J | ViP)).

F2 | Context observation

The proposed ViP statement (appendix: (J | ViP)) is still very broad, and at first instant does not directly translate to a product idea. With the ViP statement in mind and focussing on the audience, a field observation at the location were the MX3D bridge will be placed was conducted to look for a tangible and feasible problem to solve, that fits the ViP statement. While watching the behaviour of people on and around the bridge during the field observation it was found out that:

- *Groups of people turn into one stream of people.*
- *People are standing still on one side of the bridge.*
- *People almost exclusively look towards the red light district side of the bridge.*
- *Only a very small amount of people walk from or towards the opposite side of the red light district.*
- *People are trying to pass people who are standing still.*

Figure F.2: *"Think about your neighbours.." Sign near the MX3D installation spot.*

These insights formed together with the ViP statement, and the available data from the bridge (appendix: (G | Data model)), the following purpose of the lighting infrastructure and animation:

Busyness
- Number of people on the bridge (incl. avg. walking speed and walking direction).
- Number of people crossing the bridge per time period.
- Average time spent on bridge.

Activities
- Current activities (walking, standing still, leaning, jumping).
- Where are people standing on the bridge (currently and aggregated over time)?
- Where are people leaning on the handrail (currently and aggregated over time)?

Stopping people on the bridge from standing still too long or at all by making them or the bystanders (subconciously) aware of the problems they are causing with the use of light.

Individual behaviour
- Current location, walking direction, walking speed, and orientation of each individual.
- Current activity (walking, standing still, leaning on handrail).

This purpose definition is indirectly creating a link between people passing by and local society, by enhancing both their overall environment by creating less irritation, and more awareness of each other. On top of that it makes the street safer by reducing people pushing each other around, and stimulating a constant flow of the crowd with the use of data.

G Design brief

This chapter summarises all insights gathered from the preceding chapters, and formulates a goal, and design guidelines. Based on the design brief, a lighting infrastructure capable of displaying a valuable animation will be designed.

Figure G.1: *MX3D factory - NDSM Werf (Estes, 2018).*

G1 | Design guidelines - How it should be

Based on the insights gathered in the knowledge areas, the following design guidelines are formulated.

The bridge

The bridge is a show piece, so should be the lighting infrastructure. It will be one of the first uses of contextual data generated by a structure influencing its surroundings.

Light

Focussed light (brilliance) will be used on the handrails to transfer detailed information and form the main part of the animation, while semi focussed light (focal glow) on the sides of the bridge is used to assist and make the animation more natural and integrated with the structure.
Resolution and update speed of the lighting infrastructure must be high enough (60+Hz) to create clear, detailed and fluent animations, while smoothing/smearing the light will be more aesthetically pleasing and create unity. The first goal is to make the lighting infrastructure and animation functional and understandable, aesthetics has a lower priority.

Data

Data from the bridge in the topics busyness, activities, and individual behaviour will be used to control the animation on the lighting infrastructure.

Technology

Either addressable LED strip, or projectors, assisted by soft spots can be used as light sources for the MX3D bridge. A custom solution has to be created with these sources to form an integrated solution on the MX3D bridge. A central lighting controller will convert the contextual data to light data and distribute this data via ART-Net, DMX, or streaming over LAN while also taking care of power distribution for the lights.

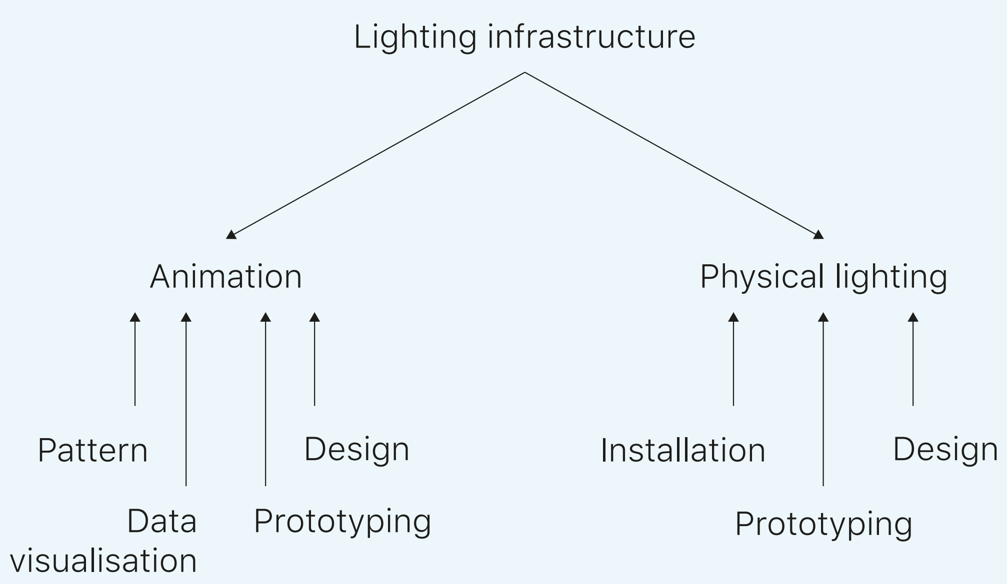
G2 | Design goal - What is should do

The assignment stated to: Develop a lighting infrastructure for the sensor-instrumented 3D-printed MX3D bridge to visualise the dynamically generated data, and take into account human interaction and experience, urban and architectural design, and smart lighting technologies.
This will be achieved by following the design guidelines and the design goal:

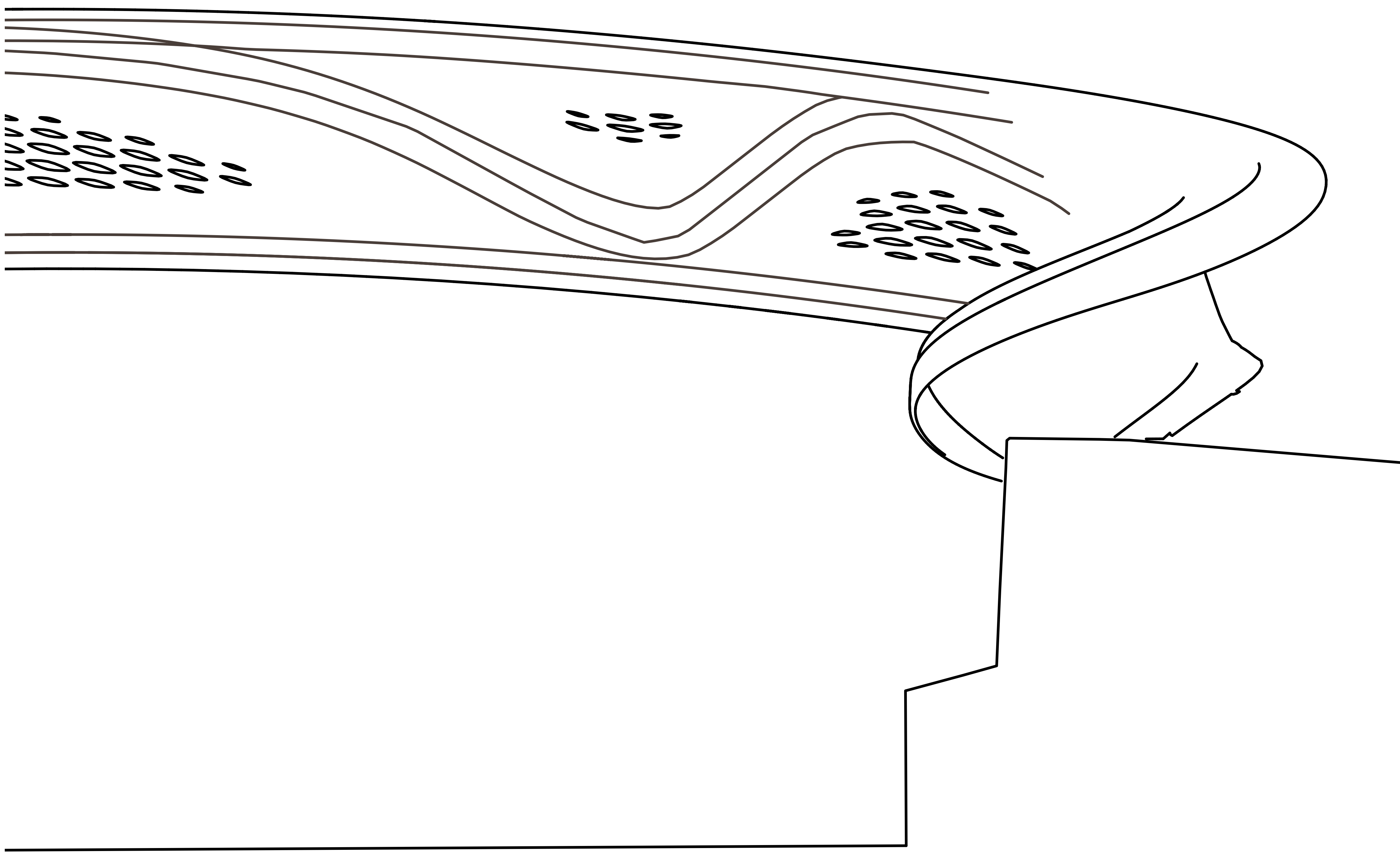
The lighting infrastructure should be an integral part of the MX3D bridge, creating a symbiosis between the structure and the light, strengthening each other. It must be able to display an animation (light) that is "stopping people on the bridge from standing still too long or at all, by making them and the bystanders aware of the problems they are causing". The animation must be driven in real time by the contextual data from the bridge to target and control the right audience.

G3 | Conclusion

The formulated design goal and insights form the preparation for the next phase were the animation and physical lighting infrastructure will be designed separately. Designing the final animation requires more exploration and defining of the variables which will be done in the next chapter. A solution has to be designed for the physical lighting to be integrated on the bridge, and enable the animation to be displayed correctly.



H Conceptualisation



This chapter will discuss the creation and development of the animation and lighting infrastructure concepts. Many ideas and principles are validated with physical models, sketches, and in software. Focussing first on the animation, different patterns are developed, data visualisation properties are determined, and prototypes are made. The physical lights are designed using the same steps.

Figure H.1: *Line drawing of the MX3D bridge, side view.*

H1 | Designing the animation (Pattern)

Now that there is a basic understanding of light, design insights on media architecture were found, the best installation places are known, and a feasible use for the data is found, it is possible to design patterns (animations) to be displayed to the audience.

H 1.1 | Approach

The statement from Chapter: (F Valuable purpose) was used as a starting point for a brainstorm with a group using how to's:, "Stopping people on the bridge from standing still too long or at all, by making them and the bystanders aware of the problems they are causing with the use of light". Clustering the outcome of this session resulted into the discovery four distinct methods to put or keep people in motion.
After the patterns were defined, they were tested by using addressable LED strips (2D).

H 1.2 | Analysis

The following four principles came out of the brainstorm session (Figure H.2):

Constant flow

Creating a constant flow with light, is expected to keep people in motion. Like a river carrying a canoe. To create the illusion of movement with light, a sequential pattern that changes over time must be used, as the brain interprets rapidly displayed consecutive frames as movement (like with a zoetrope). It is expected this will guide people in the right direction and keep them in motion.

Distracting

People standing still on the bridge to enjoy the view on the red light district which is in the middle of their field of view. Distracting these people with light from the edge of their field of vision, is expected to pull their attention elsewhere and make them move.

Annoying

Blocking observers could be forced away by annoying them with light, for example by blinding them, which is expected to set them in motion.

Public example / Spotlight

Indicating what and whom is doing wrong on the bridge by means of light could show others to not do the same. Imagine it as being put in a spotlight. This is expected to be both an example as well as setting the wrongdoer into motion.

H 1.3 | Conclusions

Four patterns were found on how to set the audience into motion when they are stalling (spotlight, annoying, and distracting). One pattern was found on keeping the audience moving.
The flow animation must be used to keep people in motion and distract them. While notify blocking people by lighting them up / annoying them with light. "Annoying" and "spotlight" are very similar animation, but with a different intent.

Figure H.2: *Participants brainstorming about the statement.*

H2 | Designing the animation (Data visualisation)

Designing an animation is a creative process, and requires real life testing and simulation to verify the wanted outcome (Courtney, 2018). To try and create the desired effect on the bridge, the most important elements of the animation were determined and quantified by testing. Literature research was done to find the important aspects of the animations.

H 2.1 | Pattern

Some aspects of the patterns described in Chapter: (H1 | Designing the animation (Pattern)), need to be better defined and quantised.

User attention

For the animations to be noticed and perceived correctly by the people on and around the bridge, it is according to Ware (2013) important that:

- *The animation should be easily perceived both in and outside of the area of immediate focal attention (whole field of view).*
- *If a person is focussed on another matter, the animation should still be visible as a reminder.*
- *The animation should not intrude so that it create annoyance.*
- *The animation should have different levels of urgency to keep the focus.*

Continuity

According to the Gestalt principle of continuity, a visualisation with smooth and continuous contours is perceived as a whole in comparison to visuals with abrupt changes. For the flow animation this means it should be smooth, natural, and continuous in order to be seen as one path over the bridge handrail. On the other hand, placing the highlight animation on the flow animation, abruptly changing its appearance, could enhance the perception of the people on and around the bridge, that the person being highlighted is a hindrance.

Direction

The flow animation should elicit a consistent perception of direction. In Europe, traffic moves on the right hand side of the road. During field research (Chapter: (F2 | Context observation)) it was clearly visible the people passing over the bridge already follows this rule. With the exception of the Red light district side of the bridge being more crowded. To amplify the need to walk on the right hand side for the sake of crowd flow, the animation should always move from right to left when standing on the bridge, perpendicular to the animation. To create direction in an animation, there must be asymmetry (Ware, 2013). In static images this asymmetry could be an arrow, or a brush stroke were there is a gradient in thickness and saturation (Figure H.4). Animating this enhances the perception of direction because the image is physically moving in the desired direction. During various tests with addressable LED strip, it was found out that a direction could be given to the light by decreasing brightness towards the intended direction. It is as if you are looking at a car from above (Figure H.3).

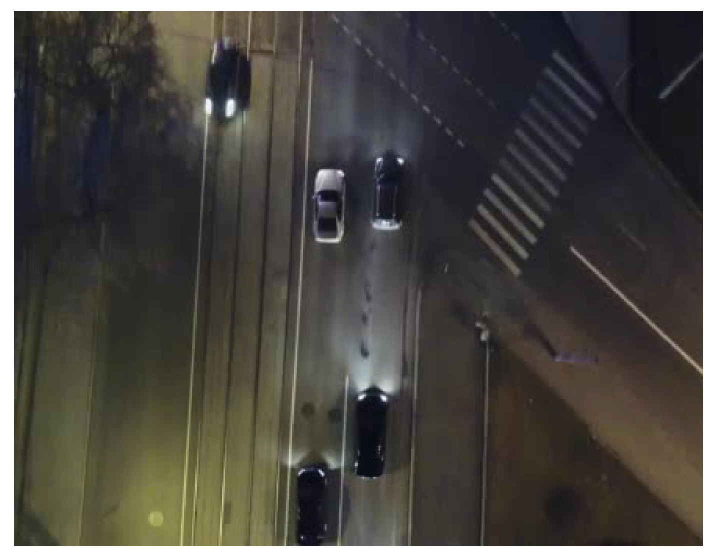


Figure H.3: *Gradient in car headlights*

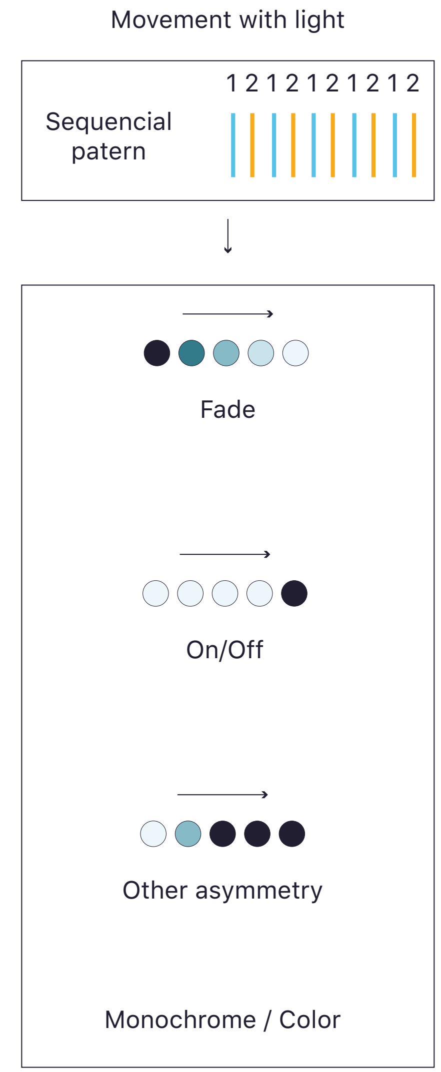


Figure H.4: *Movement with light*

Speed

The speed of the animation has two elements, the speed at which the display/animation is updated, and the movement speed of the object in the animation. The update speed (frame rate) of both the display and animation should be 50+Hz to create smooth movements even at high moving speed and prevent temporal aliasing (Ware, 2013). Temporal aliasing is most visible in movies with a low frame rate were for example the wheel of a car seems to rotate in the wrong direction, even if the frame rate of the display itself is 50+Hz. It is however important to not create flickering patterns of about 8 to 15 Hz as these could induce seizures in susceptible individuals, and create visual discomfort in general (Yoshimoto et al., 2017). As the flow animation should keep people in motion, the moving speed of the animation should be at least as fast as the average walking pace on the bridge and thus variable. Of course a minimum speed boundary must be there to stimulate movement when all the pedestrians on the bridge are stalling or walking to slow. Observing a video of the current installed bridge at rush hours gave an indication of the slowest walking speed: 2 km/h.

Light intensity

According to Ware (2013), light intensity can be described from a technical or human perspective. Luminance refers to the physically measured amount of light in variables like candela, lumen, or lux. While brightness is the perceived amount of light of self-luminous objects, but is by some people (wrongly) used to describe saturation or vivid colours. The relation between the two was documented by Stevens (1960) as:

Brightness = a*Luminance^n

Where (n) is dependent on the size of the light source, (brightness) is an arbitrary value, and (a) is a scale factor. For a point source (n) is in the vicinity 0.5, while a bigger patch of light would be around 0.3. This formula is in reality only applicable in dark isolated scenarios, but still useful to make rough estimations (appendix: (E | Brad Koerner interview)).

Contrast

To create a differences between objects, high contrast needs to be created to avoid the object from blending together.

Gamma correction

One of the basic brightness (perceived intensity) correction methods is gamma correction. This correction method takes into account that displays have a linear luminance curve, while human eyes perceive light intensity non linear (Burgess, 2018).

Details

A minimum luminance contrast ration of 3:1 should be used to separate a pattern from its background (Ware, 2013). This is applicable on in the area were the flow animation and highlight animation meet, the highlight animation should always be at least 3 times brighter then the flow animation for it to be clearly distinguishable.

Public spaces

Direct lighting in public spaces should not have a brightness higher than 100 lux average, and indirect lighting not more than 50 lux average (Koerner, 2018)(appendix: (E | Brad Koerner interview)). The flow animation on the handrail needs to be informative and not blinding, while the highlight animation is allowed to annoy the targeted people within save boundaries. This translates to a brightness of around 50 lux for the flow animation, and 100 lux for the highlight animation.

Colour

The Oudezijdese Achterburgwal is a very colourful place were the primary colours red and green are abundantly present (Chapter: (F2 | Context observation)). Red is associated with the erotic businesses in that area, while green is used for neon signs and cafes. Blue, the last of the primary colours, is frequently visible in the area in from of the emergency services, mainly the police.

Figure H.5: *Colour temperature & baby blue*

As the bridge should not be associated with either sex, beer, or the police, using saturated primary colours is not a good idea. On top of that, using multiple colours gives the impression of a fun fair, which is absolutely not what the bridge should emit. Instead, white tints have a neutral mood, and can be clearly distinct from the other colours in the area. White tints can be defined by colour temperature (Kelvin), ranging from a blueish white (6500K) to a reddish white (2000K), or mixed with primary colours to form pastel tints for example baby blue (Figure H.5)(Philips, 2018).

Conclusion

This chapter clarified and quantified the missing aspects needed to detail the animations.

The following insights were found in this chapter:

- *Use a gradient to give direction from right to left.*
- *Use white tints or pastel tints.*
- *Minimum speed of the flow animations is 2km/h.*
- *Length of highlight animation segment is 0,4m (1 person).*
- *Flow animation is repeated 5 times over the length of the bridge (2m per segment).*

The next step will be visualising the animations on paper and using LED strip.

H3 | Designing the visualisation (Prototyping)

Sketches, real life tests with LED strips, and other lights were conducted to find the best fitting animation for the MX3D bridge. Some of the visuals are displayed here, the rest in appendix: (K | Sketches (impression))

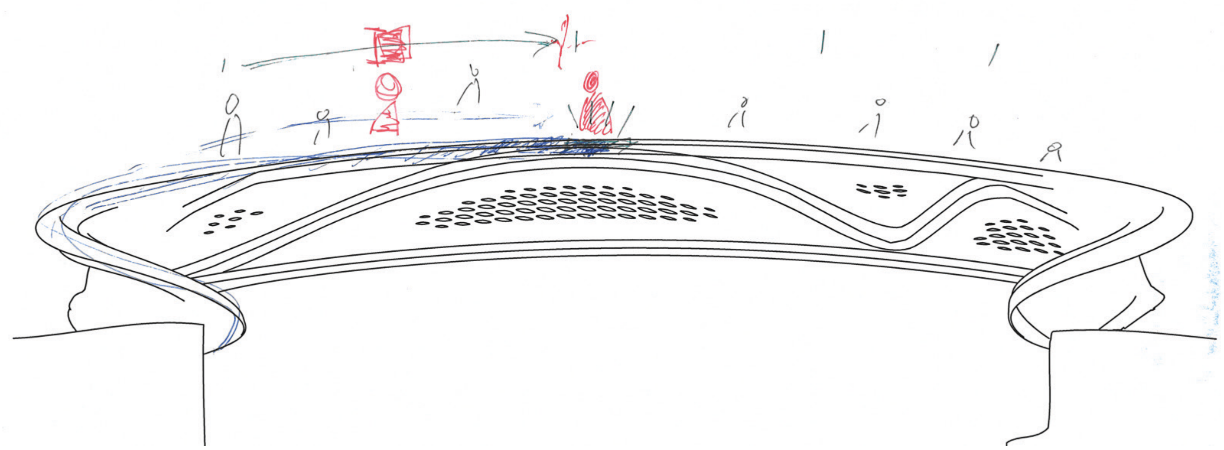
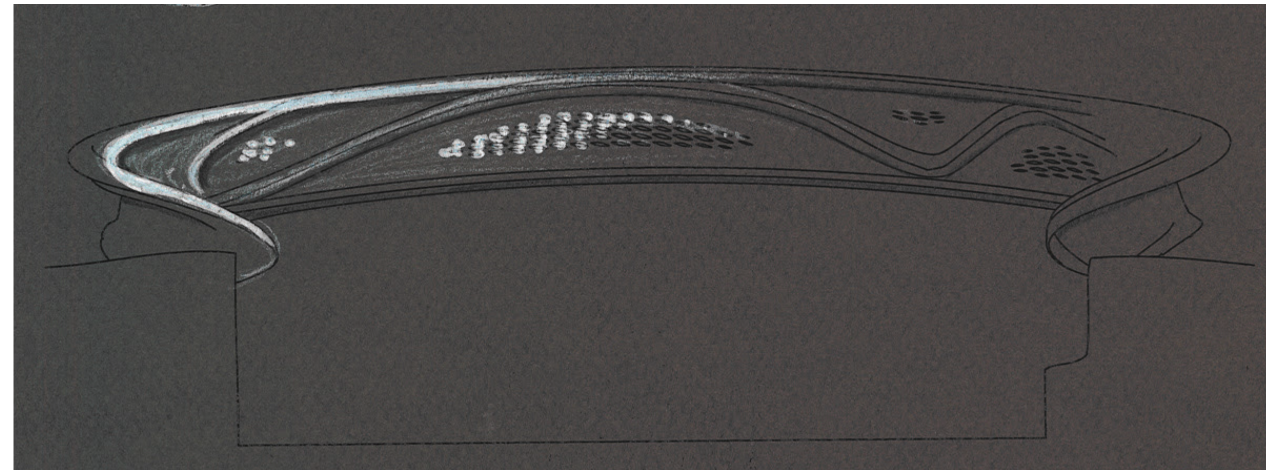
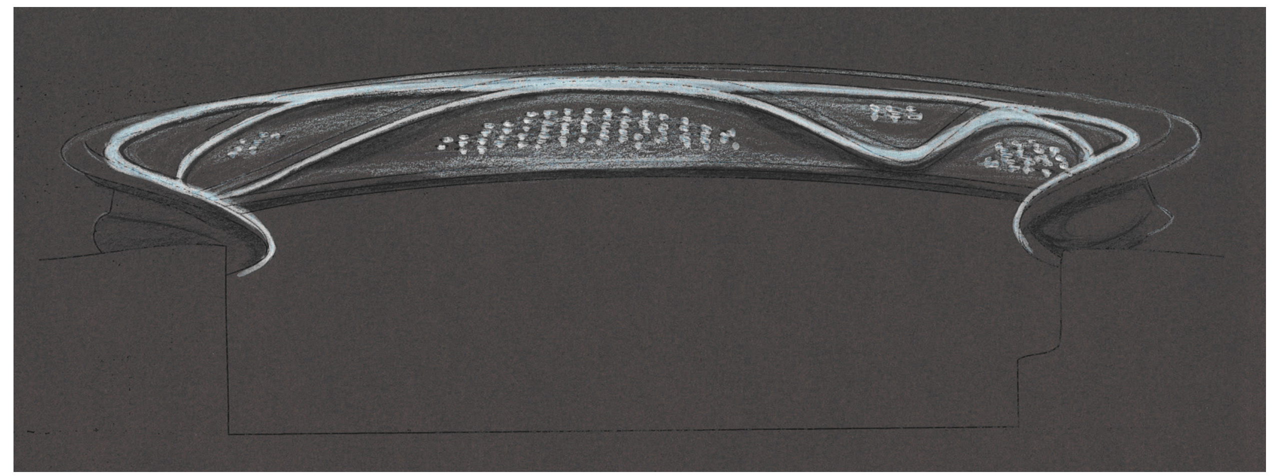
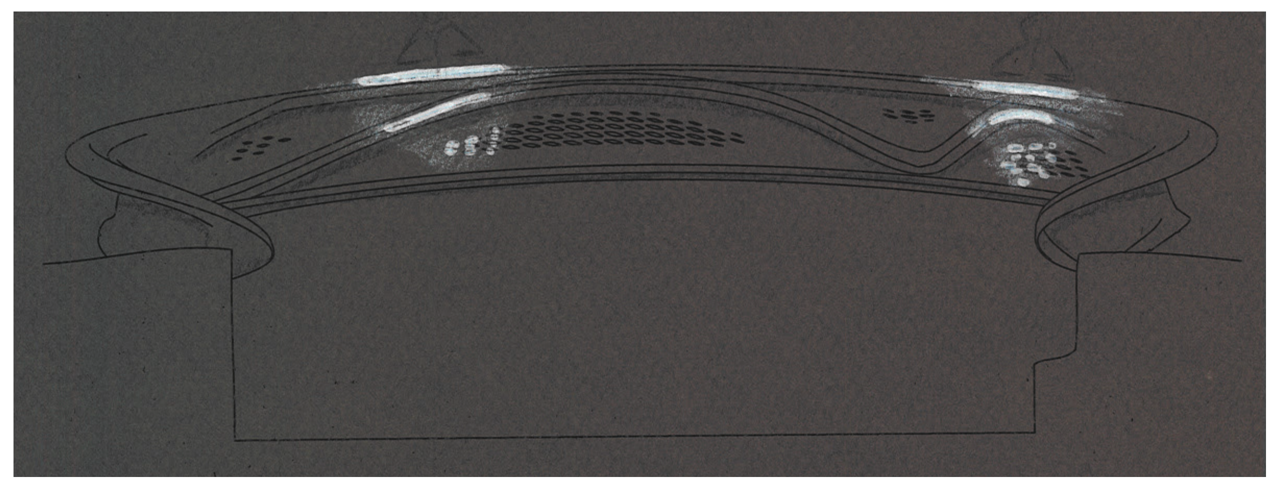


Figure H.6: *Various sketches of the animations.*







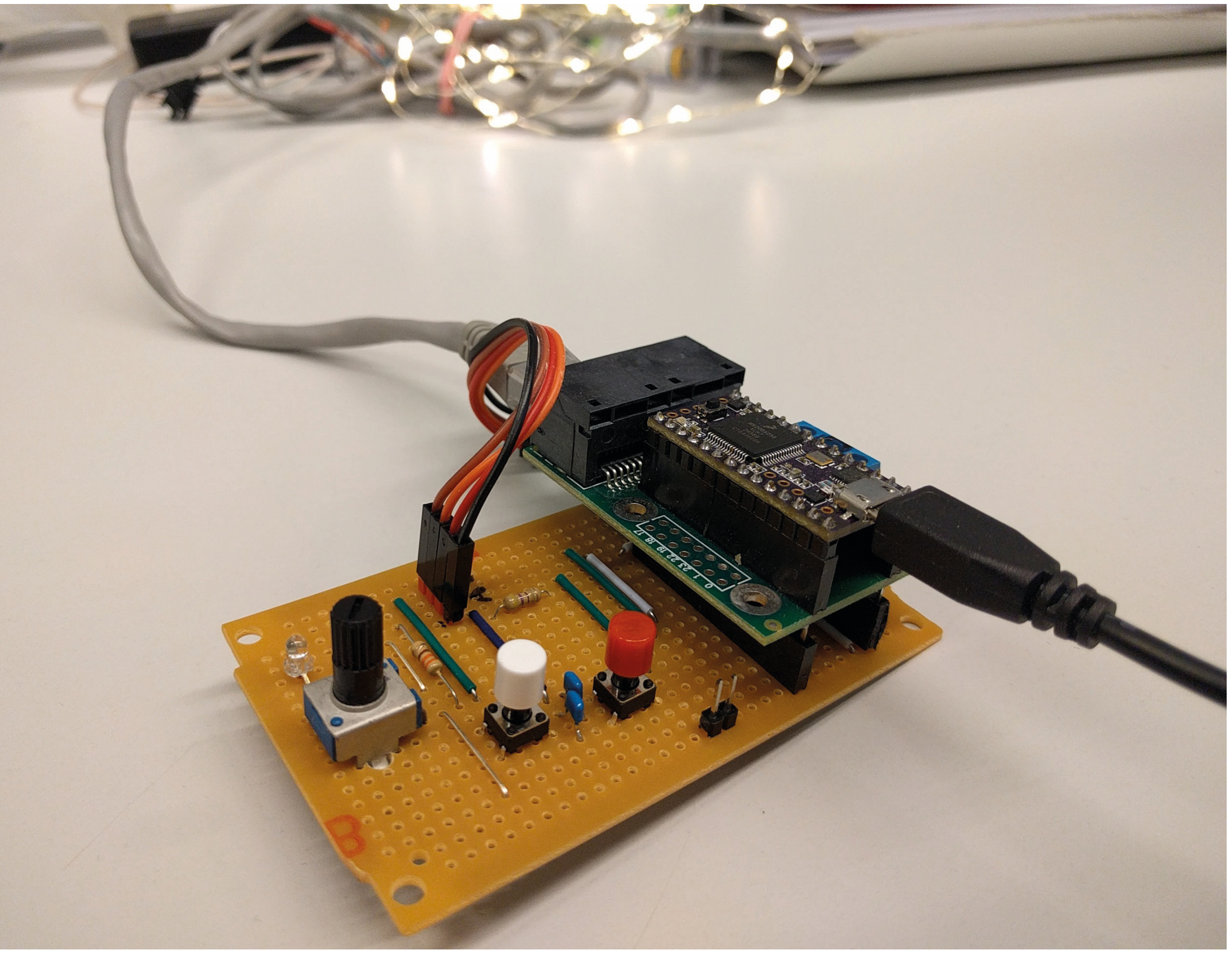
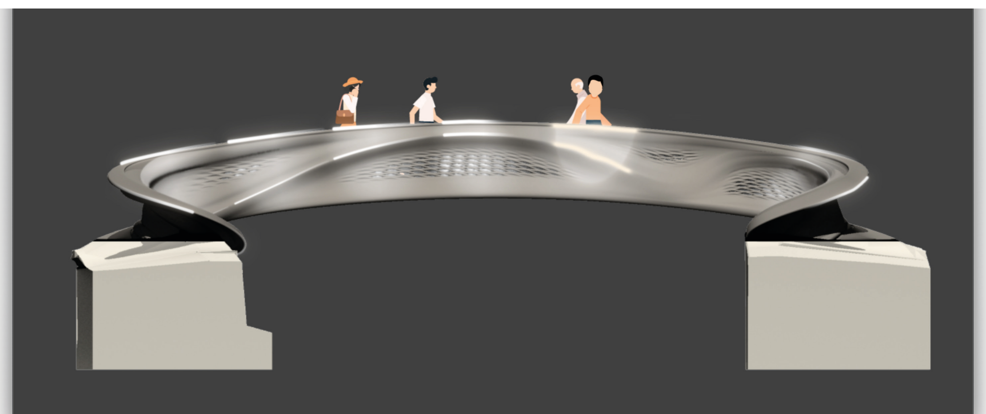


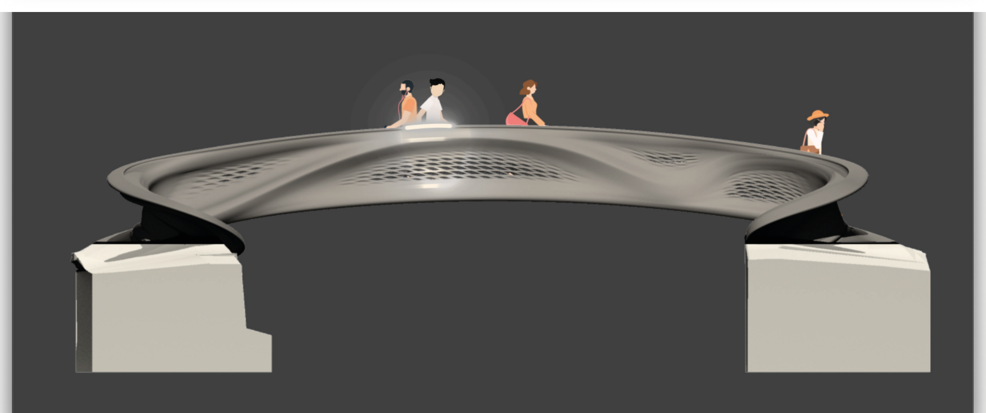
Figure H.7: *LED controller with simple user interface to change parameters during experiments. A later itteration used a small LCD to change the animation settings.*

Figure H.8: *LED strip mounted onto a 1:3 size poster of the MX3D bridge, displaying a prototype animation.*

H4 | Animation concepts

Now that the placement of the lighting, the lighting technologies, the basic patterns, the animation characteristics are known, and they are combined into fully featured animation concepts (Figure H.9), it is time to explain them in detail. appendix: (L | Animations - light only) shows supporting visuals.





Animation 1: Flow

The flow animation (Figure H.9) creates a continuous stream on the MX3D bridge with the purpose to keep people on the bridge in motion. By using a gradient sloping forward on the top of the handrail, the intended walking direction is indicated. The speed of the animation will have a minimum of 2.5km/h to stimulate people walking slower to match this speed (like driving on the highway). Otherwise, the speed of the animation is dependent on the average walking speed of people on the bridge using the data from the bridge. To make the people who will pass over the bridge get a better understanding of the animation, the outside of the bridge will have the same animation as on top of the handrail, so they can see what is happening while walking on the quayside towards the bridge. Integration with the MX3D bridge its design is also expected to be greater due to the elaborate animation.

Target audience and goal:

- *All people on the bridge (top of handrail)*
    - *Influence their walking speed and direction.*
- *The people on the quayside walking towards the MX3D bridge (outside of the bridge)*
    - *Create an understanding of the animation by watching it.*

Animation qualities:

The animation is:

- *Creating a feeling of movement*
- *(Unconsciously) stimulating the pedestrians to move*
- *Indicating a clear walking direction*
- *Indicating to walk on the right side of the bridge*
- *Indicating to not stand still*
- *Moving with a minimum speed (2.5km/h)*
- *Moving with speed that adapts to average walking speed of people on the bridge*

Figure H.9: *Left, from top to bottom: The animations: Flow, Block, and Annoy.*

Animation 2: Block

The block animation (Figure H.9) uses the flow animation as a basis with the goal to keep people in motion, and give a visual representation of the flow. When a person is standing still, the flow will be interrupted by a light bar on top of the handrail, highlighting that person like a dam in a river. The side of the bridge will show a circular light where the person is standing still, setting them in a spotlight (like on a stage).

Target audience and goal:

- *All people on the bridge (top of the handrail)*
  - *Influence their walking speed and direction.*
- *The persons standing still on the bridge next to the handrail (top of the handrail)*
  - *Set them in motion.*
  - *Show them they are blocking the flow.*
- *The people on the quayside walking towards the MX3D bridge (outside of the bridge)*
  - *Create an understanding of the animation by watching it.*
  - *An audience that is watching the persons standing still.*

Animation qualities:

The animation is:

- *Creating a feeling of movement*
- *Stimulating the pedestrians to move*
- *Indicating a clear walking direction*
- *Indicating to walk on the right side of the bridge*
- *Indicating to not stand still*
- *Moving with a minimum speed (2.5km/h)*
- *Moving with speed that adapts to average walking speed of people on the bridge*
- *Making the pedestrians aware of the person stopping the flow*
- *Putting that person in a spotlight*
- *Public shaming that person*
- *Indicating a blockade*
- *Making the blocking person feel uncomfortable*

Animation 3: Annoy

The annoy animation (Figure H.9) is only visible when people are standing still on the bridge. When that happens, slowly the light intensity of the animation will increase. If they are still standing still, a bright flashing pattern on top of the handrail will be activated, trying to chase them away. The side of the bridge will show an upward moving pattern to indicate the person standing still.

Target audience and goal:

- *The persons standing still on the bridge next to the handrail (top of the handrail)*
  - *Set them in motion.*
  - *Annoy them.*
- *The people on the quayside walking towards the MX3D bridge (outside of the bridge)*
  - *Create an understanding of the animation by watching it.*

Animation qualities:

- *The animation is:*
- *Indicating a person is standing still*
- *Putting that person in a spotlight*
- *Indicating that person is not allowed to stand there*
- *Chasing away / repelling that person*
- *Annoying that person*
- *Giving that person negative attention*
- *Indicating to not stand still on the bridge*

H5 | Intelligibility - User acceptance test

A user test (appendix: (M | User animation test - questionnair)) was conducted to evaluate the designed animations on user acceptance, understanding, and to find out what the best animation is to be displayed on the MX3D bridge. The following research objectives were formulated to do so:

	1	2	3	4
Research Objectives	Is there an understanding of the animation its intent	Is there a difference in understanding of intent between the perspectives on the bridge & on the quayside	What animation is most preffered (for both perspectives)	What animation is found most fitting the design of the MX3D bridge (for both perspectives)
	Animation qualities			
Hypothesis	It is expected the basic intent of the animations is understood by the participants. They may lack the ability to consciously recognise detailed features of the animations.	Both perspectives are uderstood the same way	It is expected the block animation will be most preferred due to it being fluent, yet notifying about the person who is standing still in both perspectives.	It is expected the flow animation will be found most fitting the design of the bridge, because it is following the shape of the bridge, and not interrupting the flow in both perspectives.

The animation qualities as described in Chapter: (H4 | Animation concepts), will be used to test the understanding of the three animations.

H 5.1 | Participant preparation

Before the test, the participants are briefly made familiar with the context of the MX3D bridge, the environment, how the bridge is used, what it looks like, and its special features by using visuals and textual explanation on a computer screen (appendix: (O | User animation test - visuals)).

H 5.2 | Test setup

In the test (appendix: (M | User animation test - questionnair)), the three different animations as described above are used, each having two perspectives (six animations in total). All answers are written down on paper by the participants themselves, while they see the animations on a 22" Dell P2210 monitor in a quiet office setting (Figure H.10).

Question one ("What is the purpose of the light on the bridge according to you? Elaborate.") is to be answered per animation. This open question is to extract the first thoughts of the participants when they see the animations, answering the first two research objectives. During question one, the 6 animations are shown one by one, the first three animations are always from the quayside perspective as that is what people approaching the bridge see first.

Question two A ("What animation do you like most? Elaborate (why)") & B ("What animation fits best with the design of the MX3D bridge? Elaborate (why)") are answered per set of three animations, giving insights for research objective three and four.

Question three ("The purpose of the animations is to either elicit a feeling of movement, or annoy people on the bridge. Do you think this is correct for all animations, or is there one or multiple animations that stand out and have no or another purpose? Elaborate on your choices (why)") tries to gain a deeper insight in the opinion of the participants, supporting all research objectives.

Three versions of the test ensured all animations were circulated (test A, B, C). Each version was conducted by five participants, for a total of 15 participants.

Figure H.10: *Test setup.*

H 5.3 | Discussion

The following research questions were answered using the results in appendix: (N | User animation test - Results).

Research objective 1 & 2:

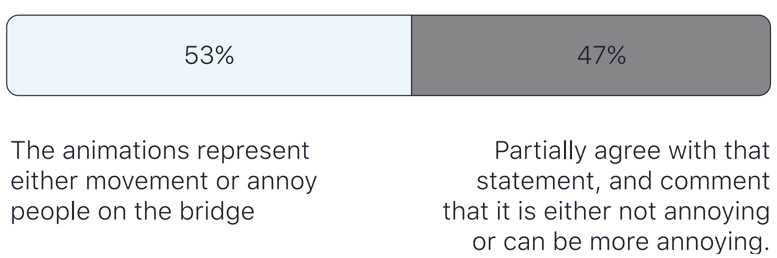
Comparing the results from question one with the intended animation qualities gave the following insights:

Flow

The flow animation has mainly been described as showing the walking direction (11 of 15 participants, Quayside)(7 of 15 participants, on-the-bridge), and with the on-the-bridge perspective also to order the pedestrians to keep walking (6/15, on-the-bridge). This means these two elements of the animation are well understood. The other key feature of the flow animation, the dynamic speed, is mentioned a lot less (4/15, Quayside)(1/15, on-the-bridge). This difference between the two perspectives may be caused by the limited field of view the participants had, and the static environment of the shown animations. The overall low score of this animation quality could be caused by the small and slowly changing speed variable, this makes seeing differences very hard.

Block

As the basis of this animation is the same as the flow animation, it is not weird that these animation qualities are rated similar. It is understood well that the animation is indicating that someone is standing still on the bridge from the quayside perspective (7/15). However, only 3 out of 15 participants mention my location, and no one mentioned they were blocking the flow on the bridge from the on-the-bridge perspective. From this same perspective, 2/15 participants mentioned the animation is ordering them to keep walking. This clearly indicated the block animation is not well understood, especially from the perspective on-the-bridge.

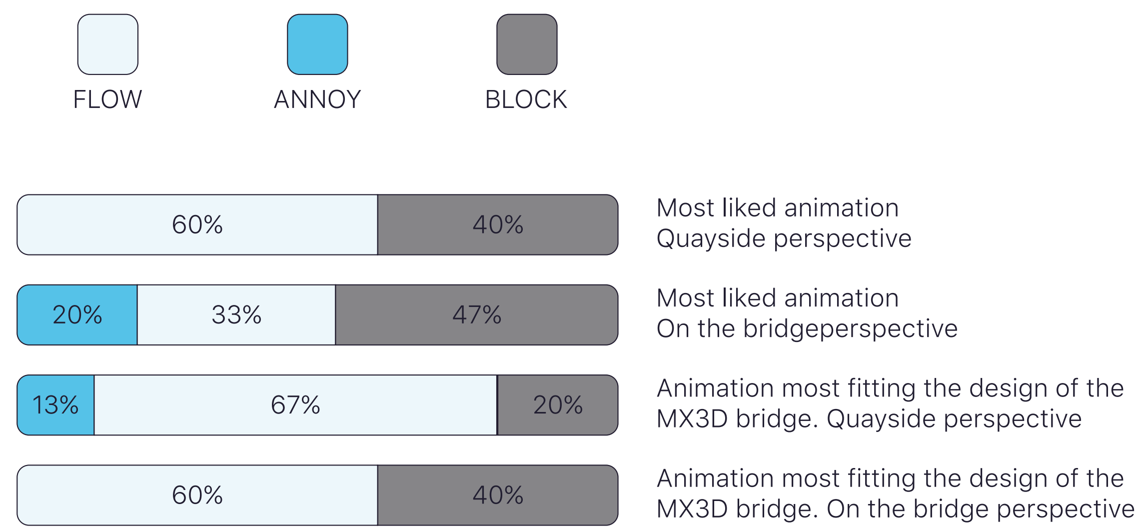


Annoy

This animation has been described as giving negative attention to the person highlighted by the animation (5/15, Quayside), and giving the order to move on and keep walking when seen from on the bridge (6/15, on-the-bridge). From the quayside perspective it is clearly better understood that there is a person standing still on the bridge (9/15) in comparison to the perspective from on-the-bridge, were only 4 out of 15 participants mentioned the animation was indicating their lack of movement.
After explaining the intent of the animations to the participants (question 3), half of them fully agreed with their intent, while the other half partially agreed with the comment that more annoyance could be created or there was no annoyance at all (left diagram). This contradicting with their first statements, and could be caused by less contrast in the displayed animation, and thus a less annoying experience.

Research objective 3:

For the quayside perspective, the flow animation is most preferred (60%) by the participants (personal). Due to it being perceived as fluent, non intrusive/disruptive, minimalistic, and following the shape of the MX3D bridge.
For the perspective on-the-bridge, the block animation is most preferred (47%) by the participants (personal). Due to it being perceived as soft, functional, average, informative, and useful. The main reason this animation scores highest is because the combination of the block functionality and softness from the flow part of the animation according to the participants reactions. This is however peculiar as the intent of the block animation was understood least of all animations.



Research objective 4:

For the quayside perspective, the flow animation is found most fitting (67%) the design of the MX3D bridge (objective), because the participants found it fluent, following and emphasising the shape of the MX3D bridge, smooth, and organic.
For the perspective on-the-bridge, the flow animation is also found most fitting (60%) the design of the MX3D bridge (objective), because the participants found it emphasising the shape, matching the lines, subtile, smooth, and organic.

H 5.4 | Conclusion

Animations
It is clear that the flow animation is best understood, most preferred by the participants, and found most fitting with the design of the MX3D bridge. This level of understanding is most likely caused by the simplicity and smoothness of the animation, and this is also why it is preferred most/found best fitting the bridge. As the participants described it:

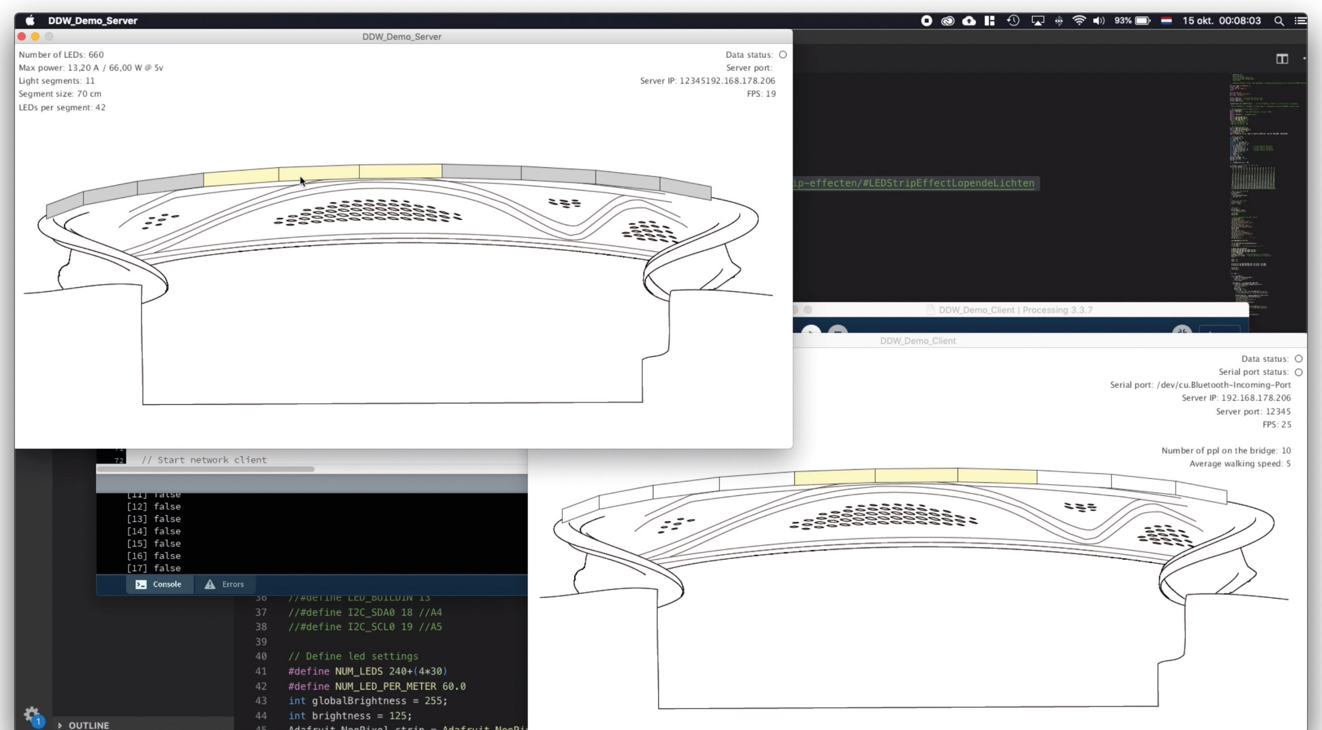
"Because it is smooth, clean and minimal - Angles".

As the variable speed of the flow animation is not understood well, it is too simple for the MX3D smart bridge project in terms of using the data in a valuable way. Therefore it is decided an additional element is needed that is understood by the audience, and makes the animation more interactive. As understanding is most important, the annoy animation is a better option then the block animation. A combination between the flow and annoy animation will provide a solution that is both understood, and will fit the bridge.

Test
It is expected the animations, especially with the perspective from the bridge, will be understood better when the test is more immersive. This can be achieved by panning the view of the animation back and forth so a wider part of the bridge and the animation can be seen. On top of that, adding moving people on the bridge and quayside will make the whole scene more dynamic. To go even a step further, virtual reality (VR) could be used to mimic the real environment as much as possible without requiring the difficulties of building and installing a physical lighting infrastructure while giving an immersive experience.

H6 | Designing the physical lighting (DDW) Demo

As a learning experience, and to find practical implications, a demo was made for the Dutch Design week 2018 with the aim to use real data from the bridge (Figure H.11). A JSON* based communication protocol was designed and tested using a server and client mimicking the Autodesk bridge server, and lighting infrastructure (Figure H.12)(appendix: (P | DDW Demo code sniplet)). Due to complications, it was unfortunately not possible to show the demo at the dutch design week with real time bridge data. It was however a good learning experience.



*"JSON (JavaScript Object Notation) is a lightweight data-interchange format. It is easy for humans to read and write. It is easy for machines to parse and generate." (Ecma International, 2017).

Figure H.11: *Server and client: The client lights up the blocks that are activated by clicking on the server UI. Programmed in Java.*

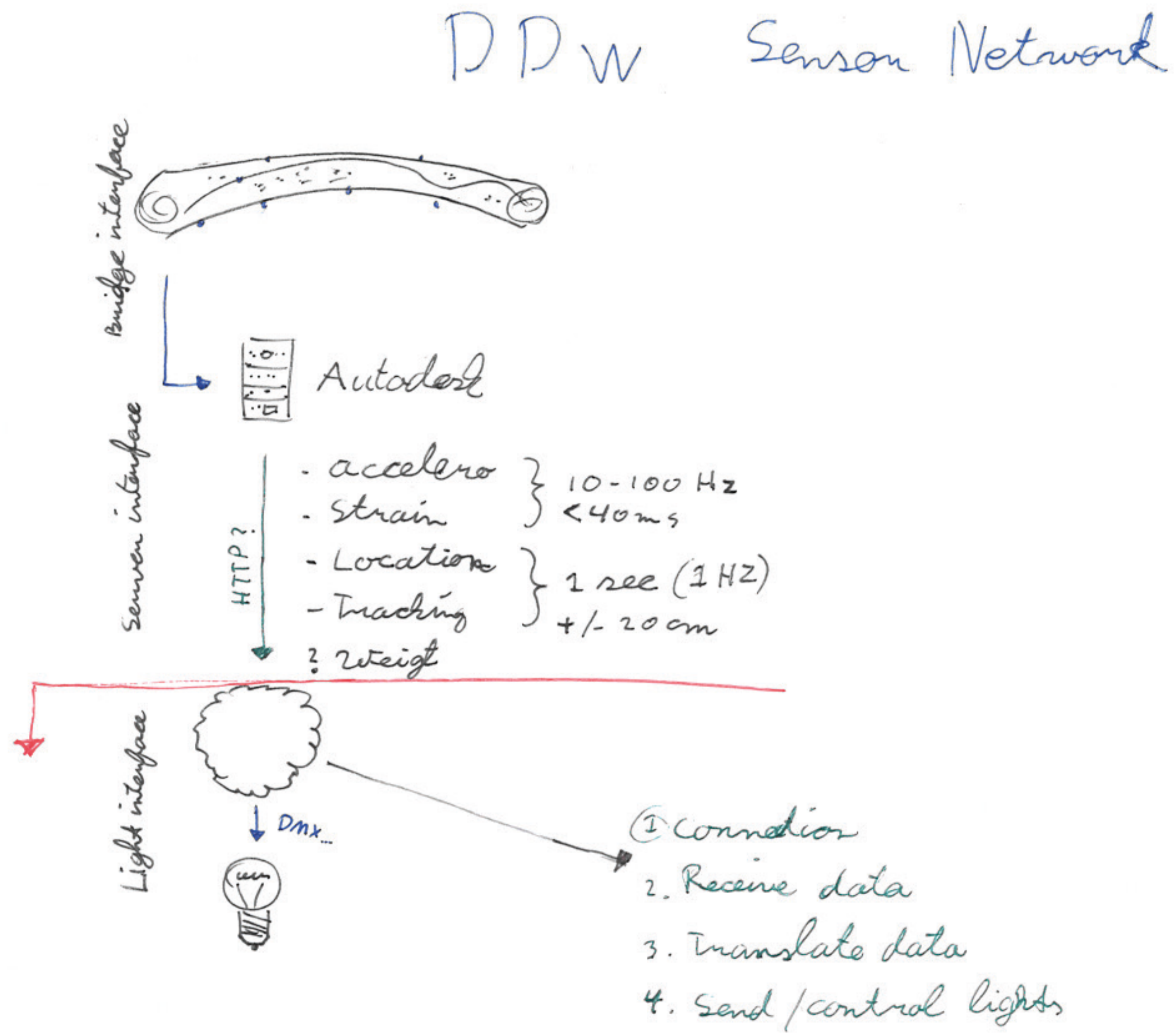


Figure H.12: *First API proposal. The latest version used JSON to get the data from the Autodesk server to a local client.*

H7 | Designing the physical lighting (Prototyping)

Prototyping the physical light was twofold. At first projection mapping in combination with a passive light guide was tested. However, light intensity was not sufficient on top of the handrail, even with the light guides. Active lighting in the form of addressable LED strip was added, and different ways of installing it on the handrail were considered. A frosted polycarbonate cover was designed that will be placed on top of the handrail.

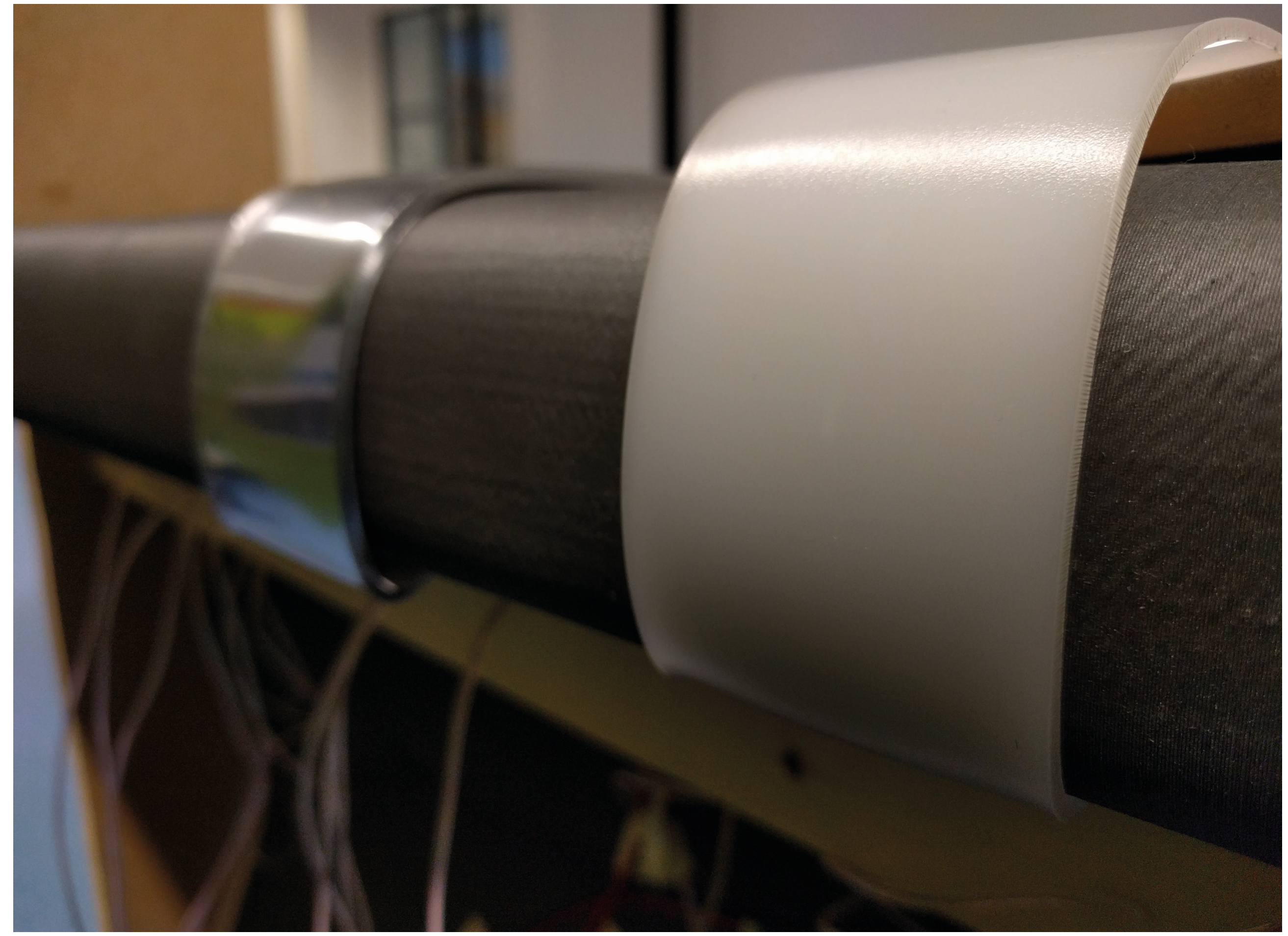
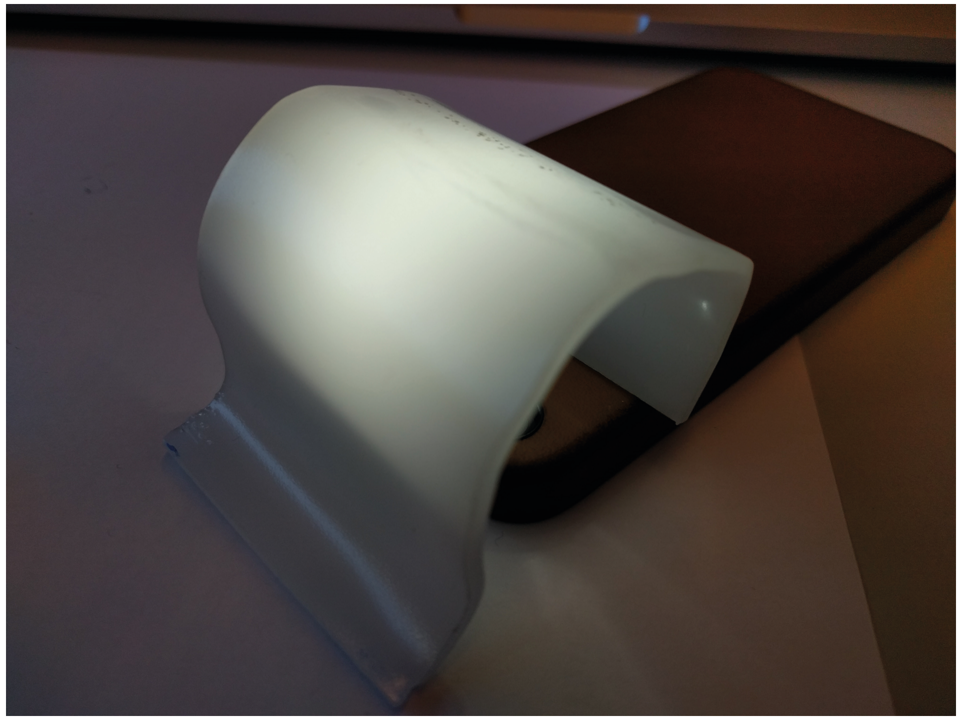


Figure H.13: *Left: Projection (mapping) tests on a print of the MX3D bridge. Right top: Light guide shape tests on a 1:1 scale bridge part. Right Bottom: 3 types of difusing material during light test.*



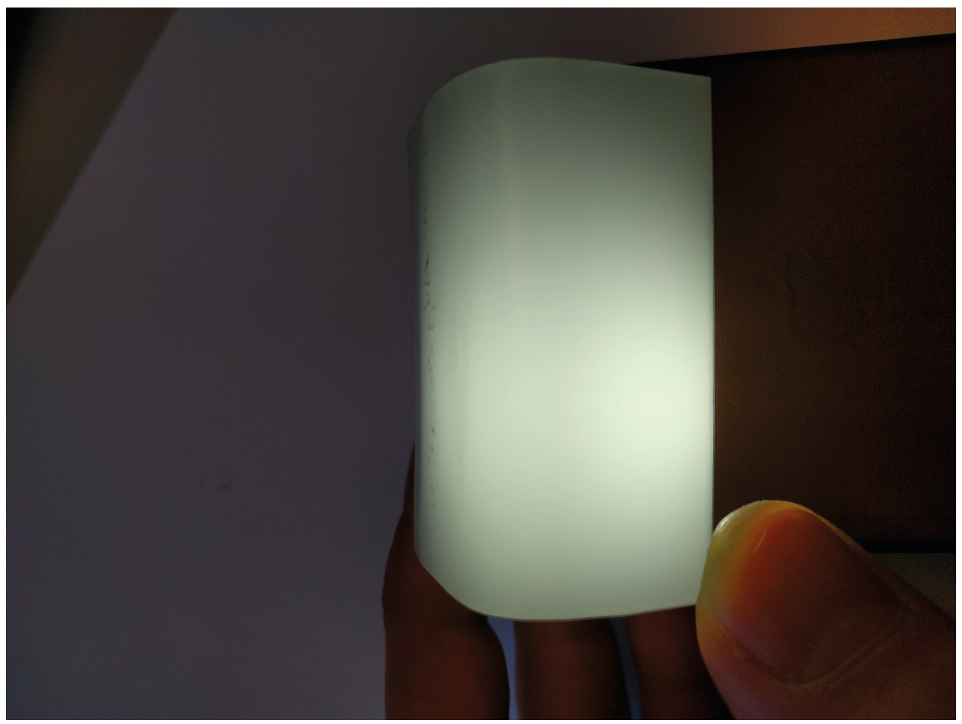


Figure H.14: *Diffusing properties of the cover.*

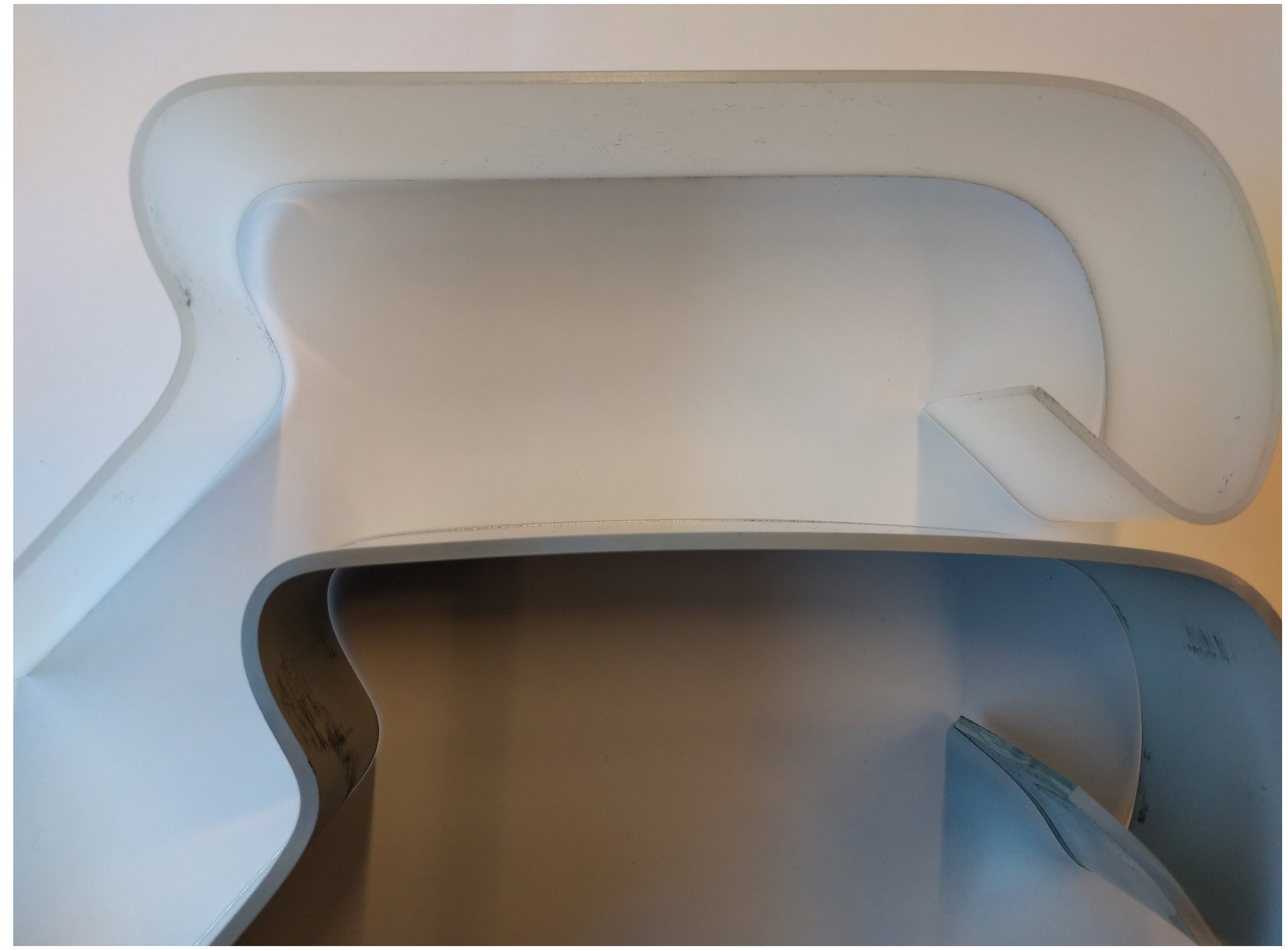


Figure I.1: *Different shape and material tests for the LED cover.*

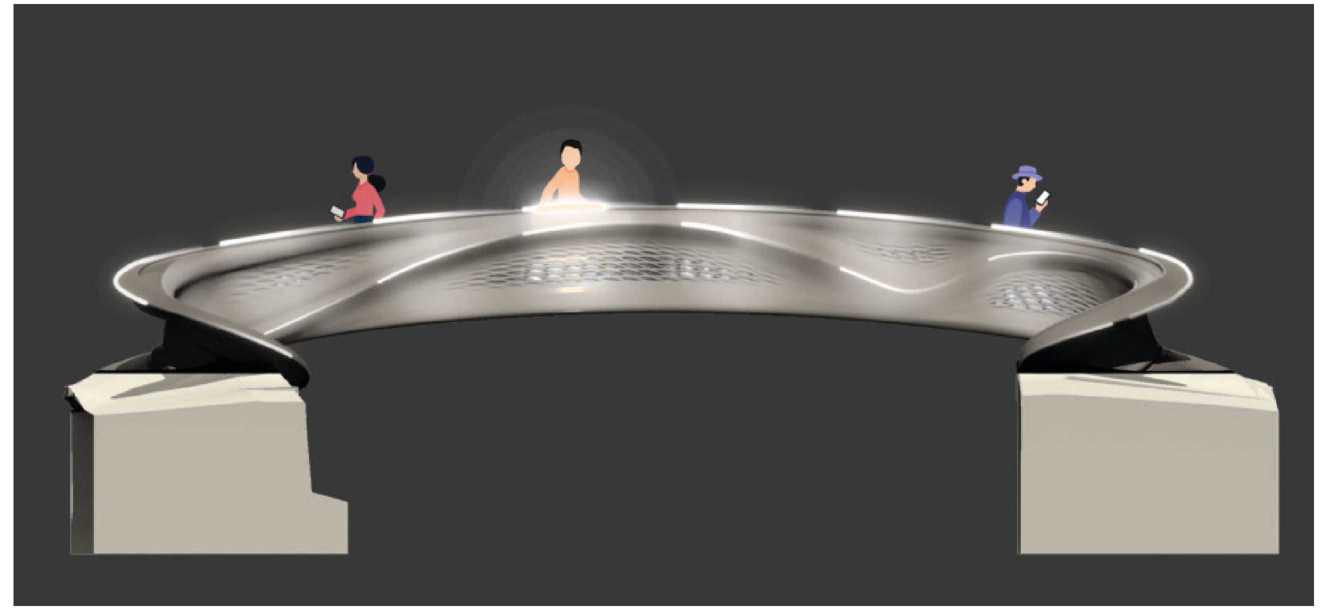
I Final concept

This chapter concludes with the final concept for both the animation and physical lighting. Combined they form a feasable and functional solution to display the data from the MX3D bridge, to the people on and around the bridge.

Figure I.2: *MX3D bridge at the DDW 2018 showing the placement of the LED strip on on side of the bridge.*

I1 | Animation

The final animation to be displayed on the MX3D bridge is a mix between the flow and annoy animation. The goal to keep or set people on the bridge in motion is fulfilled by the two parts of the animation. The constant flow following the shape of the bridge is both aesthetically pleasing and elicits a feeling of movement, direction, and speed by people on and around the bridge (Chapter: (H5 | Intelligibility - User acceptance test)). While the annoy part of the animation will set people standing still on the bridge in motion by flashes of light.



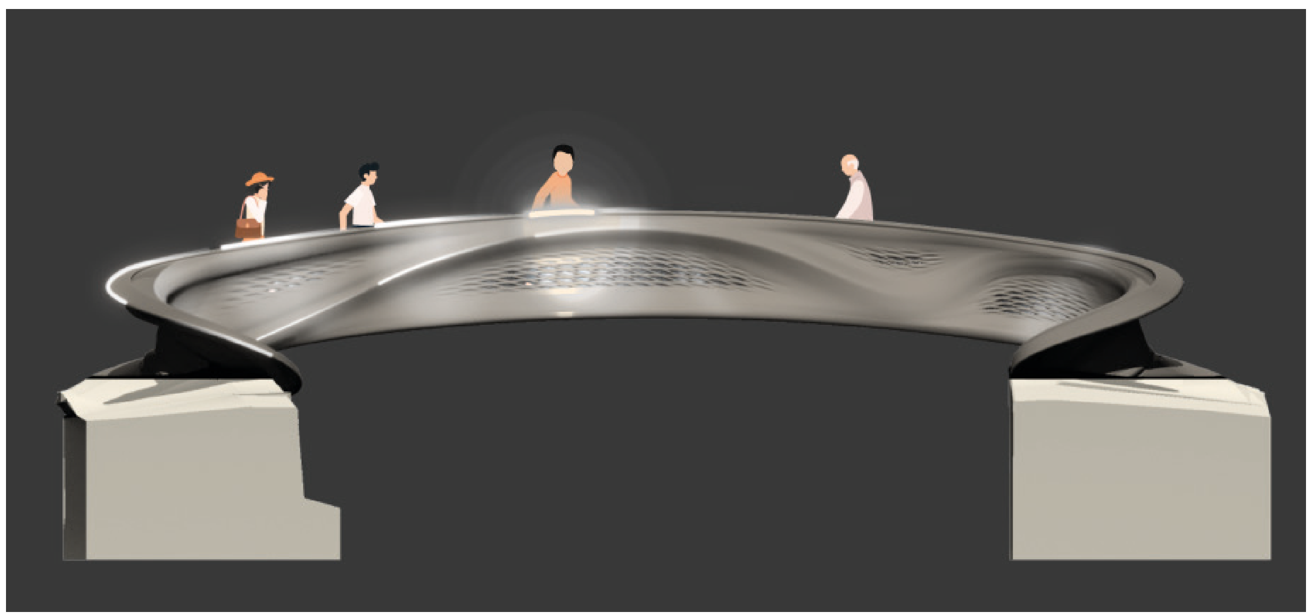


Figure I.3: *Person standing still for a long time, flow is decreased.*

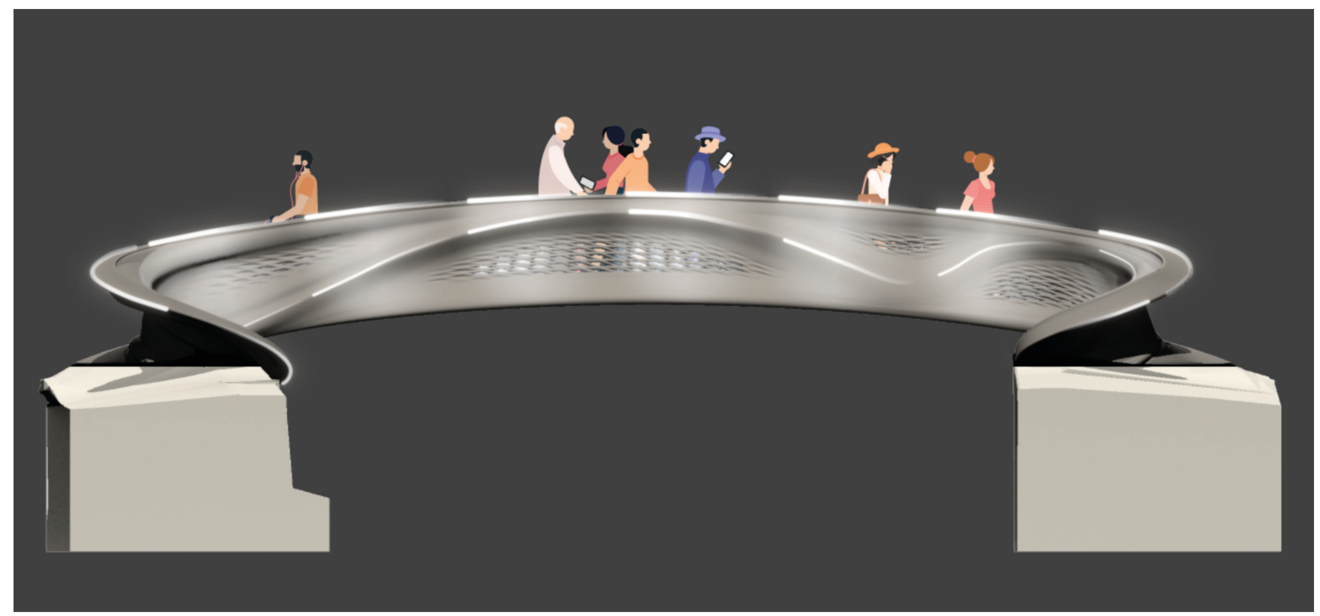


Figure I.4: *Top Person standing still. Bottom: Normal flow without people standing still.*

I2 | Physical lighting infrastructure

During experimenting with the different lighting techniques, it was found out that a combination between lighting methods was needed to created the desired animation effect with sufficient light intensity, detail, integration, and aesthetics.

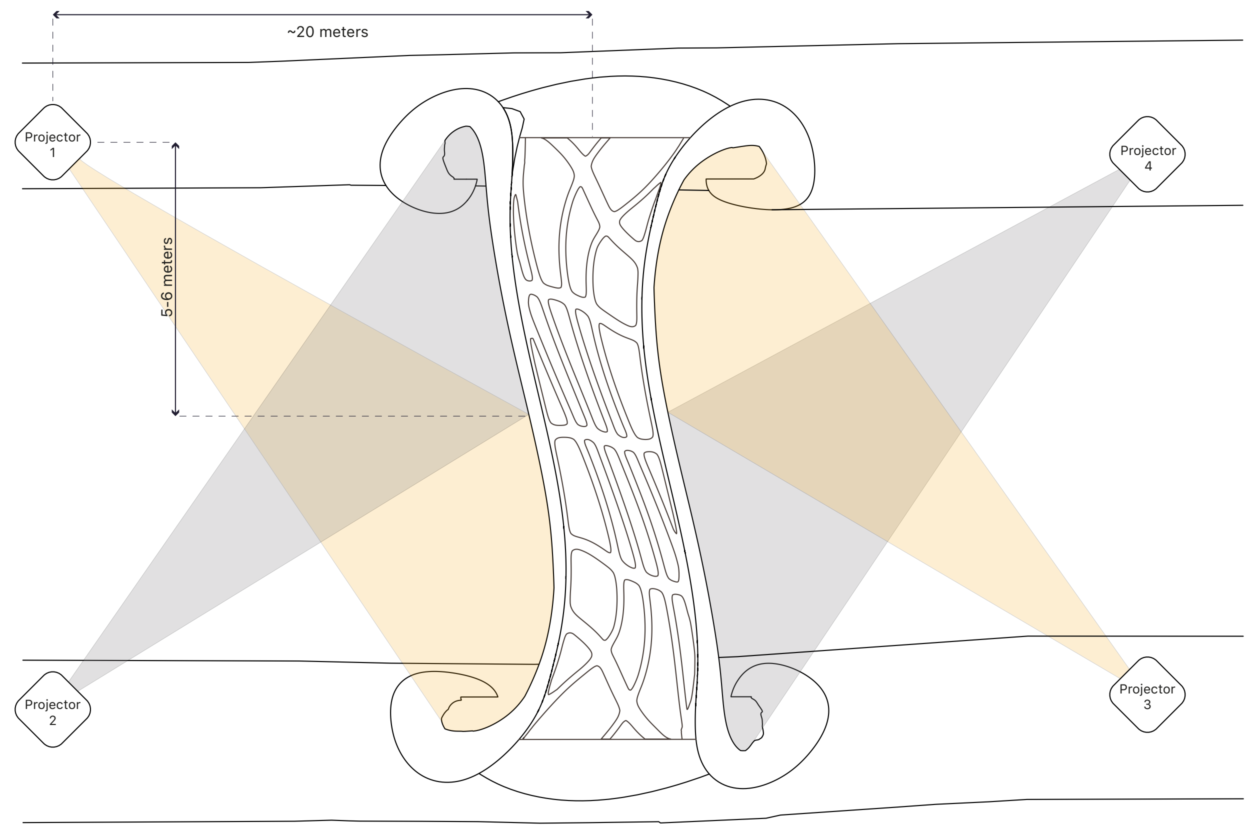
I 1.1 | Projection mapping:

Four high lumen (6.000 ANSI lumen) projectors placed around the bridge (Figure I.5) will project on both sides of the MX3D bridge, covering most of the surface. The use of projectors instead of other lighting techniques makes it possible to create detailed animations on the side of the bridge, and having the option to alter the animation with ease (for example during special events).

Using the projectors has the following benefits:

- *Resolution. High resolution means more complicated animations can be used, targeting the right audience, and following the shape of the bridge better.*
- *Ease of installation. As only four projectors are needed to cover both sides of the bridge, installation is easier compared to multiple light sources, or light sources attached to the bridge itself.*
- *Universal. As stated in chapter@@@, media architecture should change over time to stay up to date, changing the animation is almost as easy as playing a new video.*

A specific projector that seems fit is the Lumitrix IP43 rated outdoor projector (Figure I.5) (Lumitrix, 2018). This projector can also be easily mounted onto a standard pole (Figure I.5). appendix: (Q | Projection mapping technology) has additional graphics.



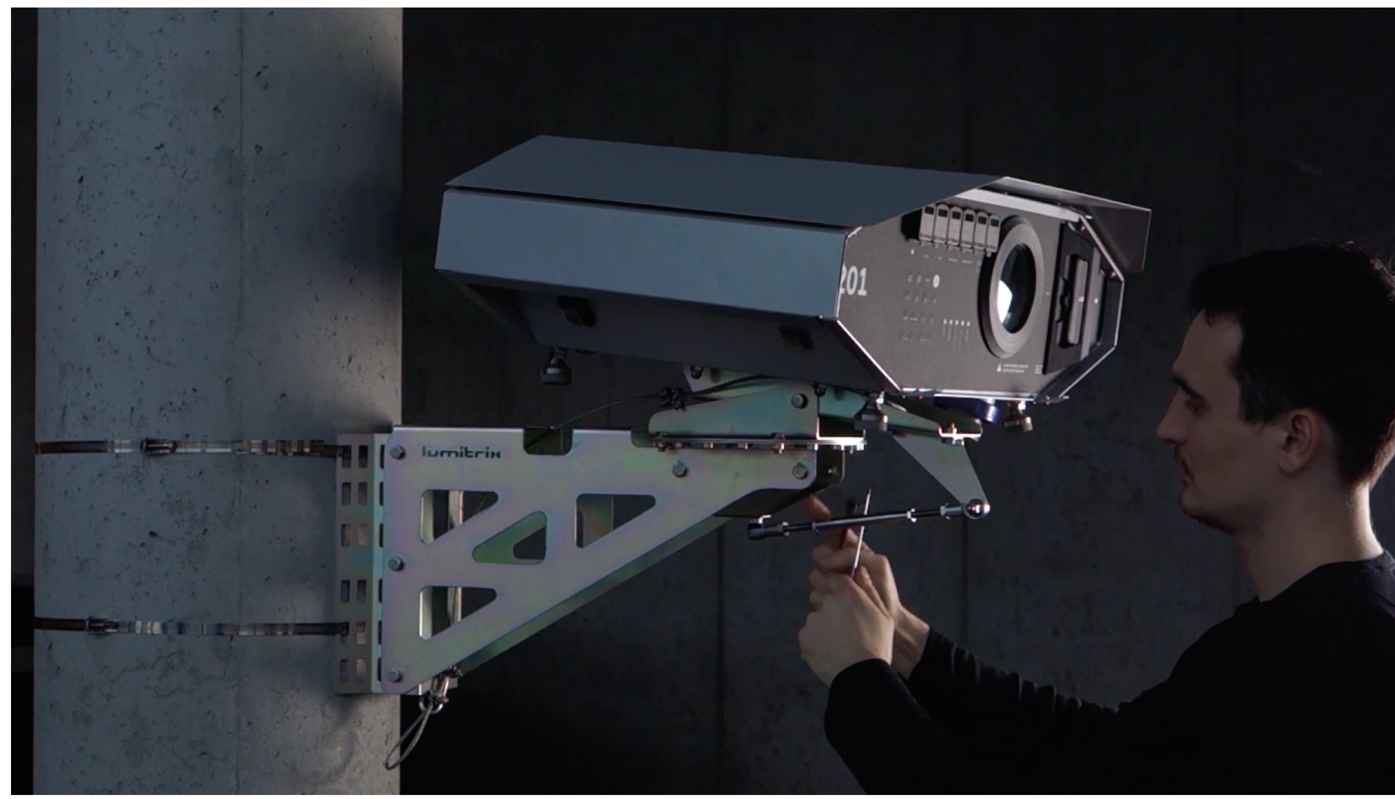


Figure I.5: *Right: Top:Projector placement, optimal distances according to manufacturer. Bottom: Lumitrix projector being installed on a big concrete pole (Lumitrix, 2018).*

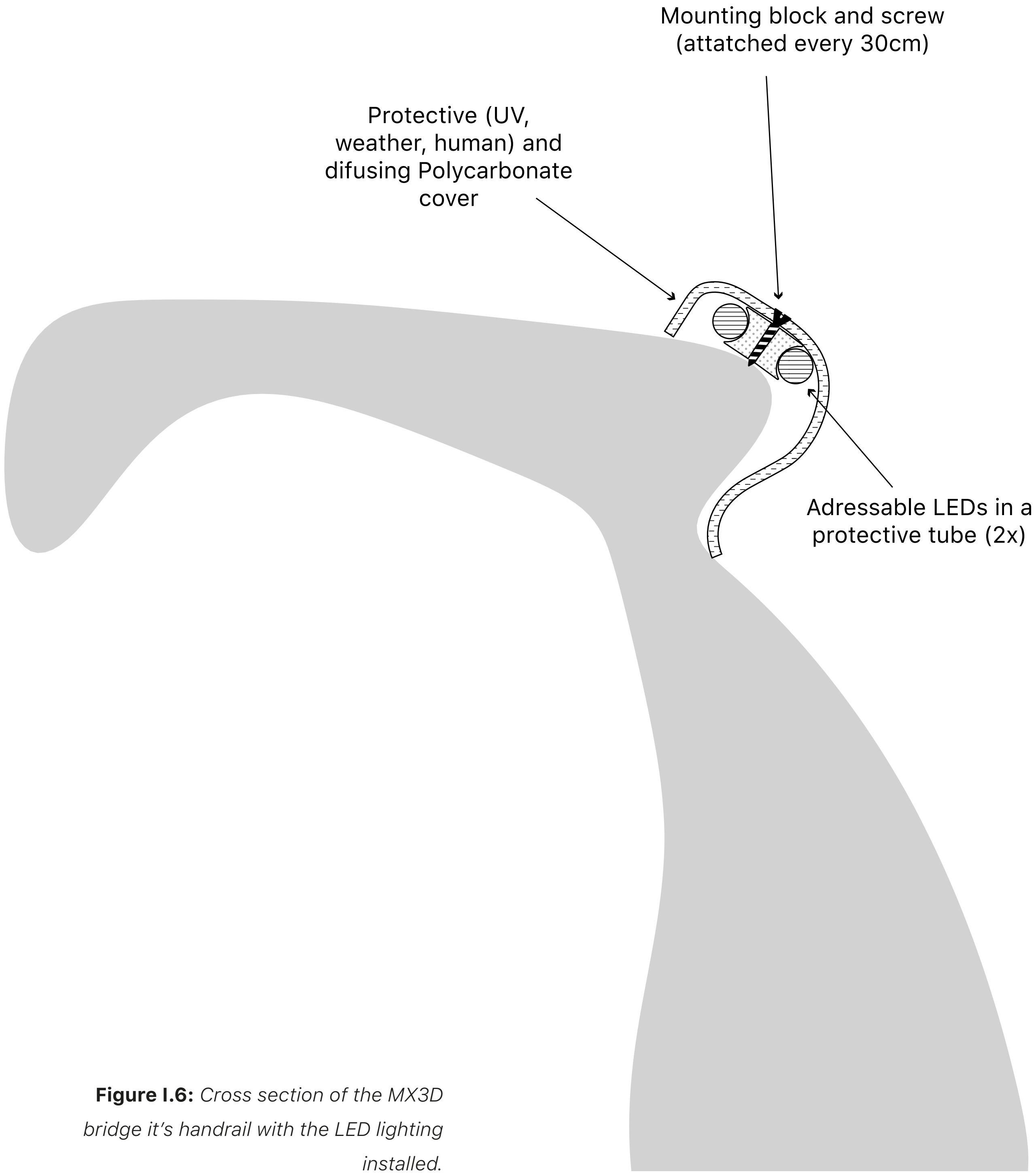


Figure I.6: *Cross section of the MX3D bridge it's handrail with the LED lighting installed.*

I 1.2 | Addressable LED strip:

The only way to get a high enough light intensity on top of the handrail, facing the people on the bridge, is by installing LED strip directly onto it (Figure I.2). These LED strips will be encapsulated by a frosted shell made from Polycarbonate (Figure@@@@) protecting them from the weather, vandalism, and other environmental factors. On top of that, the shell will defuse the light, giving the light a more natural look, and form the physical connection between the LED strip and the bridge. Figure I.6 shows a cross section of the LED assembly explaining the different parts. The choice was made to use addressable LED strip for the handrail, because of the following advantages:

- *High brightness Allowing to irritate people with light if necessary, or just create clearly visible animations.*
- *High contrast. Making the animations more clear, even in lighter environments.*
- *Viewing angle. Making it possible for both people on and around the bridge to see the animations.*

appendix: (R | Adressable LED technology) contains more visuals of the different components.

Figure J.1: *Small prototype of the extruded polycarbonate cover placed on a 3D printed piece of handrail.*

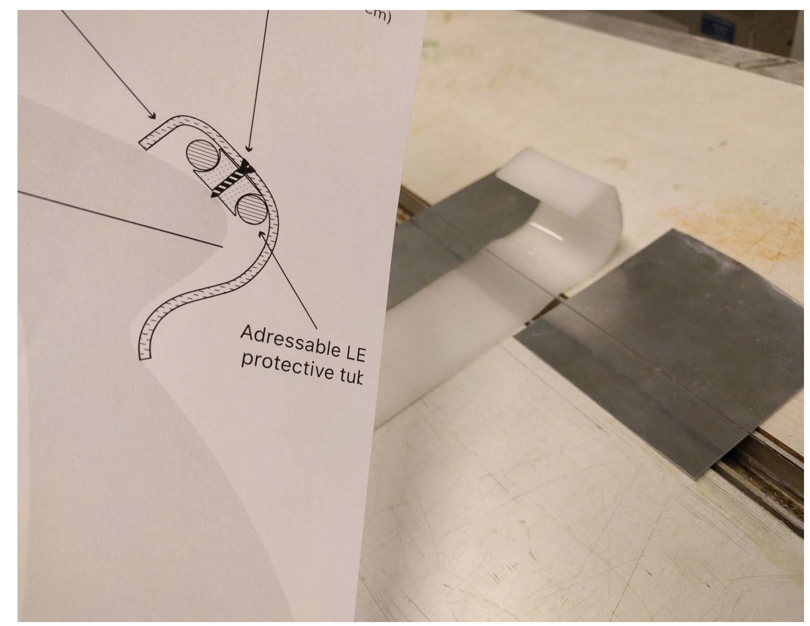


Figure J.2: *Bending (only for prototyping) of the cover (small part ~50mm). Real lenght is the same as the lenght of the MX3D bridge handrail.*

J Evaluation

This chapter will discuss the project in general, the process, and will conclude with recommendations.

Figure J.3: *Oudezijdse Achterburgwal during the evening.*

J1 | Project

The assignment was to “Develop a luminous data skin (lighting infrastructure) for the sensor-instrumented 3D-printed stainless steel MX3D bridge to visualise the dynamically generated data, while taking into account human interaction and experience, urban and architectural design, and smart lighting technologies”.

This project covers the human interaction part by having found a valuable use for the light: Stopping people on the bridge from standing still too long or at all, by making them and the bystanders aware of the problems they are causing with the use of light”. The lighting infrastructure technology is mainly discussed on a level of data transfer, analysis, and collection. Different technologies for smart lighting are presented, and the best fitting are used for the final design. Media architecture combines the bridge, context, and lighting.

Overall this project covers the parts described in the assignment, and on top of that combines them into a useful, feasible, and validated lighting infrastructure.

J2 | Process

For me, this was the most difficult project I ever did. Mainly because it started very broad, and for me the final goal was too under defined. The project made me work more step by step, setting intermediate goals, and keep focus on the bigger picture.

J3 | Recommendations

J 3.1 | Current project

The designed lighting infrastructure and animation are in a prototyping stage. More detail has to be given in the specific manufacturing of the LED lighting, the animation is to be made parametric so it can be controlled in real time by the data, the software controlling the animation and receiving the data has to be written, and other detailing has to be done. On top of that the data analysis by Autodesk and the sensor network itself are in their early stages and far from finished, resulting in insecurities about what data will be available for sure. For this project however, there was sufficient information to develop a proof of concept lighting infrastructure.

J 3.2 | Future projects

This is one of the first projects discussing the real time use of structural data for the direct benefit and influence of the people in/on the public structure. An opportunity comes forth to develop a standardised approach to design uses for this type of systems. This project and other could function as use cases to start the development of this approach. The basic steps looking back at this project would be as follows:

- *Context analysis: What, whom, where are we dealing with.*
- *Data analysis: What data is available (after analysis).*
- *Problem definition: What problem needs to be, and can be solved by using the available data (based on context analysis).*
- *Problem solution: Find the best way to solve this problem while using the data to actuate something (could be light).*
- *Validate solution: A more realistic setting will bring unexpected things to light.*
- *Iterate: Fix or change accordingly.*
- *Repeat: Validation has to be done during the time it is active, the context or data might change over time.*

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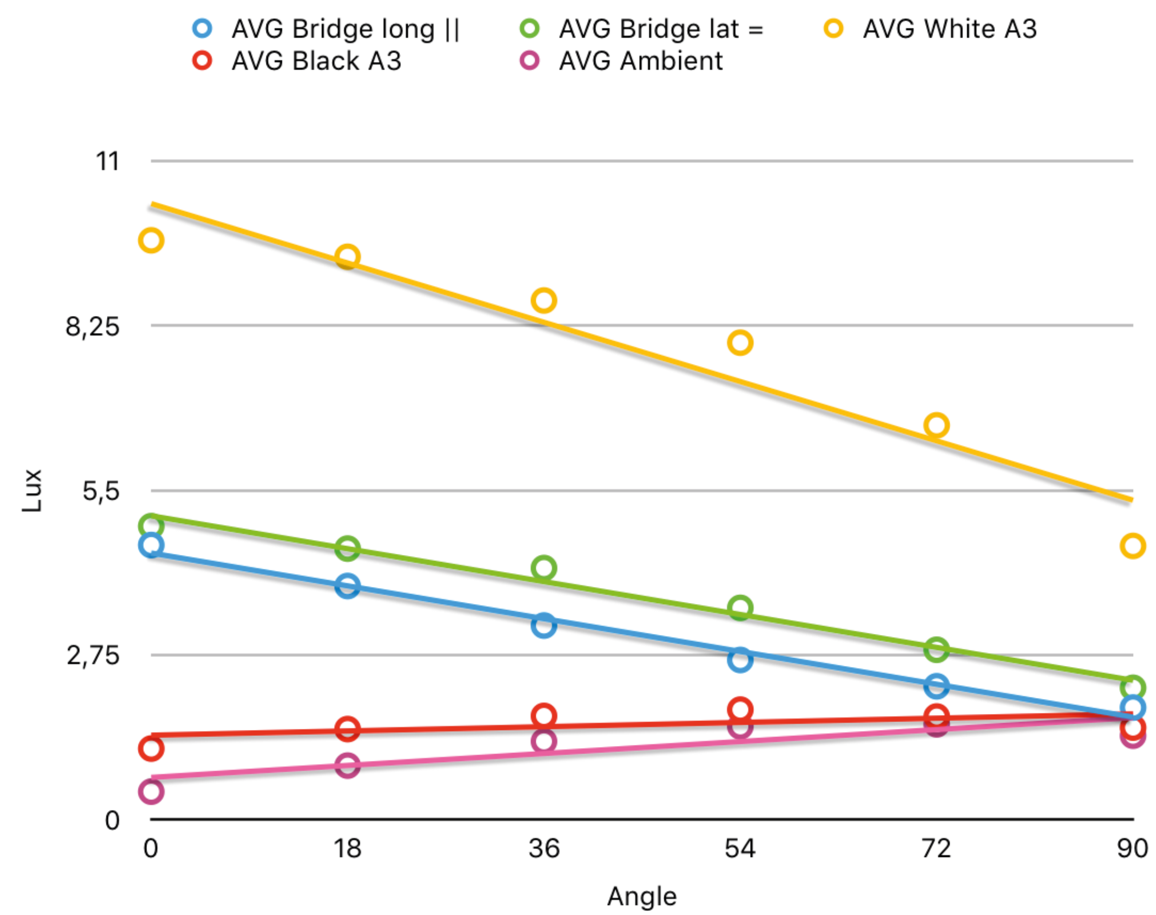
Appendix

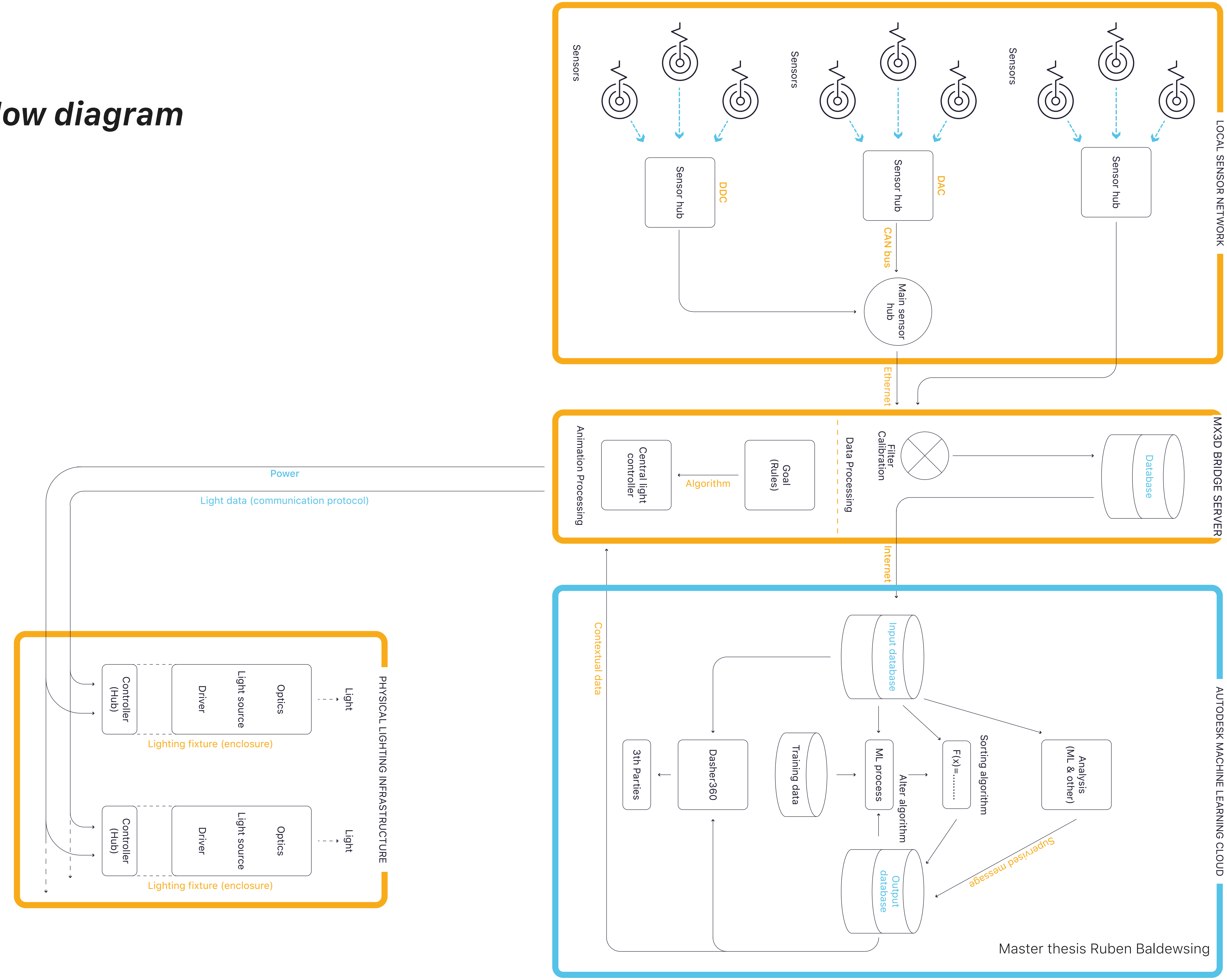
A | Light reflectance test results

Light reflectance bridge (lux)

Angle	90	72	54	36	18	0	Average % reflected per sample
Angle	90	72	54	36	18	0	
Ambient black A3 #1	1,42	1,64	1,60	1,34	0,90	0,50	
Ambient black A3 #2	1,38	1,54	1,51	1,27	0,90	0,43	
AVG Ambient	1,40	1,59	1,56	1,31	0,90	0,47	
White A3 #1	4,43	6,59	8,02	8,71	9,92	9,91	
White A3 #2	4,71	6,58	7,91	8,63	8,88	9,44	
AVG White A3	4,57	6,59	7,97	8,67	9,40	9,68	
White A3 corrected	3,17	5,00	6,41	7,37	8,50	9,21	
Black A3 #1	1,54	1,71	1,85	1,74	1,53	1,22	
Black A3 #2	1,53	1,73	1,82	1,72	1,49	1,15	
AVG Black A3	1,54	1,72	1,84	1,73	1,51	1,19	
Black A3 corrected	0,14	0,13	0,28	0,43	0,61	0,72	
Black A3 % Reflected	4,26	2,60	4,37	5,77	7,18	7,82	5,33
Bridge longitude #1	1,84	2,22	2,67	3,36	4,00	4,71	
Bridge longitude #2	1,90	2,23	2,66	3,12	3,80	4,46	
AVG Bridge long ‖	1,87	2,23	2,67	3,24	3,90	4,59	
Bridge long corrected	0,47	0,64	1,11	1,94	3,00	4,12	
Bridge long % Reflected	14,83	12,71	17,32	26,27	35,29	44,73	25,19
Bridge latitude #2	2,37	3,07	4,02	4,91	5,54	6,23	
Bridge latitude #3	2,03	2,60	3,05	3,49	3,51	3,57	
AVG Bridge lat =	2,20	2,84	3,54	4,20	4,53	4,90	
Bridge lat corrected	0,80	1,25	1,98	2,90	3,63	4,44	
Bridge lat % Reflected	25,24	24,92	30,89	39,31	42,65	48,15	35,19
Average % reflected bridge							30,19
Average % reflected per angle	14,77	13,41	17,52	23,78	28,37	33,57	21,91



B | Data flow diagram



C / Sensor list

Category		General information					Raw data exploration		
Main use	Data type	Sensor	# sensors	Placement	Data	Unit	Momentary patterns (one sample)	Hourly patterns	Daily patterns
Structural									
	Both	Accelerometer	30	See figures	Acceleration	mm/s2	Vibrations at specific points Vibrations in handrail Vibrations in deck Vibrations of the whole bridge Are people walking over the bridge: yes/no	Walking direction Tracking a person on the bridge Waling speed Recognise trafic next to the bridge	Average walking route Average walking speed Recognise sceduled trafic events
	Both	Straingauge	82	See figures	Strain	ε	Stress in a specific point on the bridge Strain in a specific point on the bridge Stress of total bridge Strain of total bridge Division of stress over points Division of strain over points Stress safe for stress limits: yes no Strain safe for strain limits: yes/no Location of people	Changes in stess Changes in strain Average stress Average strain Most visited location on the bridge	
	both	Load cells	4	On the four corners of the bridge, see figures	Weight	Kg	Total Weight of (people standing on) the bridge Load in a specific cell Division of load over 4 cells Load of people on bridge Load safe for structure: yes/no Most people are standing on X side/spot Deformation of total bridge (whitout people on it)	Change in weight/load Average weight/load Min/max load Load hotspots Most bussy spot on the bridge	Busiest moment of the day Number of people crossing a day Average amount of people crossing a day
	Structural	Inclinometer (Gyroscope)	10	See figures	Angle	°	Angle at specific points Angle in handrail Angle in deck Angle of the whole bridge	Change in angle Average angle Min/max angle	
	Structural	Thermometer	4	Cornices, bridge center top & bottom	Temperature	ºC	Temperature of bridge structure Difference in temperature throughout the bridge Difference weather and bridge temperature Temperature safe for structure: yes/no Temperature safe for touch: yes/no	Temperature change of the bridge Average temperature of the bridge	
	Contextual	Ultrasonic	3	Underside bridge, center and edges	Distance	cm	Height of water/waves		
Environment									
	Both	Temperature	4?	Nearby buildings or in swirls	Temperature	ºC	Weather at that moment Temperature of weather Hot/cold weather Apparent temperature (humidity & wind speed) Normal temperature for day/month: yes/no	Average temperature Change in temperature Temperature forecast (trend) Compare predicted vs actual temperature	Normal temperature for day/month: yes/no Average temperature Change in temperature Temperature forecast (trend) Compare predicted vs actual temperature Exeption in day
	Both	Pressure	4	Cornices, bridge center top & bottom	Pressure	Pa	Barometric pressure	Change in pressure Average pressure	Change in behaviour on the bridge due to environmental conditions
	Both	Humidity	4	Cornices, bridge center top & bottom	Humidity	%RH	Relative humidity	Change in humidity Average humidity	Change in behaviour on the bridge due to environmental conditions
	Contextual	Sound	6	Ends and under handrails	Sound	dB (RMS)	The decibel level High/low sound level	Busyness Fights Average noise level Min/max noise level	
	Contextual	VOC sensor	3	Underside bridge, center and edges	Gasses (CO2, CO, NOS)	‰ µg/cm3	Air quality at that moment	Change in air quality	Change in behaviour on the bridge due to environmental conditions
	Contextual	Light	7	At center under handrail, in swirls at both ends	Ambient light	Lux	Day/night time amount of ambient light		Change in behaviour on the bridge due to environmental conditions
	Contextual	Rain	4?	Nearby buildings or in swirls	Rain gauge	mm	Rain: yes/no Amount of rain fall		Change in behaviour on the bridge due to environmental conditions
	Contextual	Wind	4?	Nearby buildings or in swirls	wind speed wind direction	m/s N/E/S/W	Wind: yes/no The wind speed The wind direction		Change in behaviour on the bridge due to environmental conditions
Audience									
	Contextual	Capacitive?	?	On top of the handrail	Touch	yes/no + where			
	Contextual	IR camera over bridge	4	Neighboring buildings looking down into bridge	-	# of people + direction + behaviour + ML/AI training + etc	Number of people around a sensor node	Walking speed Walking direction Walking route Detailled tracking Number of people in the area Time spend at one spot	Average walking route Average walking speed Busiest moment of the day Number of people crossing or passing a day Most common stopping locations Time spend standing still Interest in a specif spot
	Contextual	IR camera under bridge	2	Under both ends of the bridge looking longitudonally as in Pier 9 bridge	Waves, canal condition (frozen etc), rodents, boat traffic, vandalism	-			
	Contextual	Wifi / Bluetooth	?	Around and on the bridge	-	# of people + direction	Number of people around a sensor node	Walking speed Walking direction Walking route Detailled tracking Number of people in the area Time spend at one spot	Average walking route Average walking speed Busiest moment of the day Number of people crossing or passing a day Most common stopping locations Time spend standing still Interest in a specif spot
City									
	Contextual	Social (media)	-	-		-	Social mood in the city Happenings Accedents Busyness Trafic etc		
	Contextual	Events	-	-		-	Special events like: Party, openings, exclusive deals, etc		
	Contextual	POIs	-	-		-	Musea, events, restaurants, infrmation points, hospitals, etc		
	Contextual	Environment	-	-		-	Detailed lockal weather reports, trafic		

D | Autodesk interview

Progress

- *Current status of the Pier9 bridge.*
- *Insights useful for MX3D bridge.*
- *Insights in data and machine learning.*
- *Data insight examples.*
- *Difficulties: Sensor placement, noise, false positives.*
- *Future vision (why make a smart bridge?).*
- *Current status of smart bridge.*

Sensors

- *Which sensor will be used for what purpose?*
- *How are the sensors attached to the bridge?*
- *Experienced difficulties?*

Data

- *What are the steps in the process of data collection?*
- *What insight do you want to gain from the sensor data? Both short term and long term?*
    - *Structural insights.*
    - *Personal insights.*
    - *Societal insights.*
    - *Environmental insights.*
- *Resolution. Precision of data insights?*
- *Crowded bridge. What can you measure?*
- *Data ownership and privacy.*

Digital twin

- *Role?*
- *What data is used (input/output)?*

Machine learning

- *What do you want to and what is possible to achieve with the self-learning algorithms?*
- *How is the bridge 'smart'?*

Actuation / Data & insights "displaying"

- *How will these insights be used (Pier9 & MX3D bridge)?*
- *Future vision.*

Other

- *MX3D on location (monitoring building).*
- *Who is the project owner, responsible for data collection on the MX3D bridge?*
- *Human influence / control / role in the smart system.*

E | Brad Koerner interview

Creating a lighting infrastructure in general

- *What are the steps you use in creating a lighting infrastructure?*
- *Difficulties in the process.*
- *How do you stay innovative?*

Integration into architecture

- *What is the most important part of integration?*
- *Elaborate on "light as a material".*

Light sources

- *Dos and don'ts*
- *New Innovative light sources.*

Light patterns and animations

- *From goal / vision to light.*
- *Evaluation of goal.*
- *Light with temper > make people do something instead of informing only.*
- *Make people move / not stand still.*

Ideas for the MX3D bridge

- *Do you see major obstacles on the MX3D bridge?*
- *Do you see opportunities / solutions?*
- *Comments?*

F | Viberlight interview

Questions:

Technology

- *Light intensity*
- *Dimensions*
- *Power requirements*
- *Assembly / installing*
- *Shapes*

Possibilities

- *Examples*

Application on the MX3D bridge

- *Possibilities*
- *Impossibilities*

Prototyping and testing

- *Samples*
- *Testing on sight*
- *Testing in the lab*

Notes:

Technology

- *Bending radius = max 10mm. If smaller light dots will appear. 20mm or more is preferred.*
- *Light source is laser (RGB or other substitutes are possible).*
- *One laser per fiber gives a slight gradient in light intensity. Two laser per fiber @@@opheven@@@ this effect, and give the possibility to create a (moving) gradient in different colors.*
- *Bendable in three directions.*
- *Normally installed in polypropylene (PP), polyethylene (PE), or transparent PVC, tubes. Ranging from 1-5mm diameter.*
- *Laser controller accepts 24-230v input, and is controllable by DMX.*
- *Controller and laser modules (12) fit in a 15*30*40 installation box.*
- *Bare fiber connector is 10mm diameter with plug, 4mm diameter when welded.*
- *2mm diameter fiber tube combination is perceived as 2 cm diameter light line.*
- *Amsterdam light festival 2 laser fiber was 57meter long.*

Possibilities

- *Floor lighting*
- *Replacement for LED strip lighting*

Application on the MX3D bridge

- *6 fibers zigzag (at 60º angle) alternating to create movement.*
- *1 fiber with two lasers (red and blue are best visible) to create a moving color gradient.*
- *Installation is most difficult, fiber is fragile.*
- *Normally fiber is placed in a tube in a "goot" on a flat surface (2D / 2,5D), encapsulated in epoxy.*
- *People can not pull the fiber.*
- *Mill a @@goot@@@ into the bridge for the fiber.*
- *Use a special UV resistant PVC tube (need to be manufactured, but possible).*

Prototyping and testing

- *On bridge testing for light reflection, installation, attachment, and placement is preferred.*
- *Samples for lab testing are available on request.*

G | Data model

		Section 1				Section 2					Section 3	
Optional	Category	Data wanted	Lvl 1 metadata	Derived data	Lvl 2 derived data	Sensors available	Real time data point	Direct / Derived sensor data	In current data model from Autodesk	Expected to be possible to do on the MX3D bridge	Not available because	Can be made available by / Possible solutions
	Busyness											
•		Number of people on the bridge (incl. avg. walking speed and walking direction)	People	Current number of people on the bridge		Load sensors	Yes	Derived	Yes	Yes		
•					Count of entrances	Load sensors	No	Derived	No	Yes	Not in the Pier9 system	This will be made possible with the 4 IR cameras
•					Count of exits	Load sensors	No	Derived	No	Yes	Not in the Pier9 system	This will be made possible with the 4 IR cameras
•				Speed & Direction	Track individuals	Accelerometers	Yes	Derived	No	No	Too many people, noise too high, resolution too low	Use of other tracking technologies like: machine vision, BLE beacons, better software.
•		Number of people crossing the bridge per time period	People				No	Derived	Yes	Yes		
•				Current number of people on the bridge		Load sensors	Yes	Derived	Yes	Yes		
•					Count of entrances	Load sensors	No	Derived	No	Yes	Not in the Pier9 system	This will be made possible with the 4 IR cameras
•					Count of exits	Load sensors	No	Derived	No	Yes	Not in the Pier9 system	This will be made possible with the 4 IR cameras
•		Avg. time spent on bridge	People				No	Derived	No	No		
•					Track individuals	Accelerometers	Yes	Derived	No	No	Too many people, noise too high, resolution too low	Use of other tracking technologies like: machine vision, BLE beacons, better software.
	Global Activities											
•		Current activities (walking, standing still, leaning, jumping, ...)	People				Yes	Derived	Training	Unknown		
•				Walking		Accelerometers	Yes	Derived	Training	Unknown	Not in the ML algorithm from Autodesk	If the noise/signal ration is good enough, the ML algorithm could recognise this data. At the moment this data can be derived from the temporary computer vision system.
					Walking speed	Accelerometers	Yes	Derived	Training	Unknown	Not in the ML algorithm from Autodesk	If the noise/signal ration is good enough, the ML algorithm could recognise this data. At the moment this data can be derived from the temporary computer vision system.
				Standing still		Accelerometers	Yes	Derived	Training	Unknown	Not in the ML training algorithm from Autodesk	If the noise/signal ration is good enough, the ML algorithm could recognise this data. At the moment this data can be derived from the temporary computer vision system.
				Leaning on the handrail		Accelerometers + strain gauges	Yes	Derived	Training	Unknown	Not in the ML training algorithm from Autodesk	If the noise/signal ration is good enough, the ML algorithm could recognise this data. At the moment this data can be derived from the temporary computer vision system. + this data has two sensor inputs.
•				Jumping		Accelerometers	Yes	Derived	Training	Unknown	Not in the ML training algorithm from Autodesk	If the noise/signal ration is good enough, the ML algorithm could recognise this data.
		Where are most people standing on the bridge (currently and aggregated over time)?	People			Load sensors	Yes	Direct	Training	Yes	Not in the ML training algorithm from Autodesk	If the noise/signal ration is good enough, the ML algorithm could recognise this data.
•				Track individuals		Accelerometers	Yes	Derived	No	No	Too many people, noise too high, resolution too low	Use of other tracking technologies like: machine vision, BLE beacons, better software.
		Where are people leaning on the handrail (currently and aggregated over time)?	People	Strain / leaning		Strain gauges	Yes	Derived	No	Yes	Sensors not in the Pier9 system	It is part of the lvl 2 metadata "leaning on the handrail" + Strain sensors in the handrail of the MX3D bridge can be directly used for this data.
	Individual behaviours											
•		Current location, walking direction, walking speed and orientation of each individual	People				Yes	Derived	No	No		
•					Track individuals	Accelerometers	Yes	Derived	No	No	Too many people, noise too high, resolution too low	Use of other tracking technologies like: machine vision, BLE beacons, better software.
•		Current activity (walking, standing still, leaning on handrail)?	People				Yes	Derived	No	No		
•					Track individuals	Accelerometers	No	Derived	No	No	Too many people, noise too high, resolution too low	Use of other tracking technologies like: machine vision, BLE beacons, better software.

H | Light sources

Type	Source name	Notes	Number of colour sources	Size	Communication protocol	Lighting method	Resolution	IP rating	Beam angle	Luminous flux	Total power (Watt)	Update rate (Hz)	Mounting method
LED strip	**Multi channel LED strip**	Need separate controller	1-5	~10mm * ~3mm * 1-10m	Proprietary	Direct	MEDIUM	IP67				60+	Custom fixture
	Addressable LED strip	Need separate smart controller	1-5	~10mm * ~3mm * 1-10m	Proprietary	Direct	HIGH	IP67 (questionable) or None				60+	Custom fixture
	Individual controllable LEDs	Need separate smart controller	1-5	36/78mm * 36/18mm * 5/9mm	Proprietary	Direct	HIGH	IP67 (questionable) or None				60+	Custom fixture
	Single channel LED strip	Need separate controller	1	18mm * 18mm * 280mm - 4970mm	Driver dependent	Direct	MEDIUM LOW	IP67	120°	380 lm/m – 1210 lm/m	6-15/m	60+	Custom fixture
	LED bar		1-4		DMX	Indirect	LOW	IP67					Bolting
Stage lighting	**Flood**	Light up the scenery	1		DMX	Indirect	VERY LOW	IP67	170°				Bolting
	Soft spot	Soft highlights	1-5		DMX	Indirect	LOW	IP67	170°				Bolting
	Profile spot	Focussed light with different shapes	1-5		DMX	Indirect	MEDIUM LOW	IP67	170°				Bolting
	Beam lights	Semi focussed light	1-4		DMX	Indirect	LOW	IP67	170°				Bolting
	GoBo projector		1-5	~400m * ~300mm * ~400mm	DMX	Indirect	MEDIUM	IP65	-	7 * 650-2250 lm	409W		Bolting
	Laser DJ projector		1-3		DMX	Indirect	MEDIUM	None					Custom enclosure
Other	**(DLP) Projector**		-		HDMI / LAN / etc	Indirect	VERY HIGH	None			300	30-60	Custom enclosure

I | Lighting control protocols

Protocol name	Notes	Intended use	Maximum number of universes	Maximum number of sub channels / devices	Maximum signal distance (Perfect reception) (meter)	Number of wires	Signal type	Wireless	Signal resolution per channel (bit)	Bitrate	Refresh rate (all channels) (Hz)	Reference
DMX512		Entertainment	1	512	1.200	3	Digital	N	8 (16)	250 Kbit/s	44	(Luna & Torres, 2006)
Wireless DMX512		Entertainment	1	512	910	-	Digital	RF	8	250 Kbit/s	44	(Lumenradio, 2017)
eDMX	DMX over Ethernet	Entertainment	10 (100)	512		8 (Ethernet)	Digital	WIFI (optional)	8 (16)	-	HIGH	(Lux Lumen, 2018)
sACN	Modular	Entertainment	-	-	-	8 (Ethernet)	Digital	WIFI (optional)	-	-	HIGH	(ESTA, 2009)
Art-Net	Modern standard	Entertainment	32.768	512	-	8 (Ethernet)	Digital	WIFI (optional)	8	-	HIGH	(Artistic Licence Holdings Ltd, 2017)
KiNET	Philips version of sACN & ART-Net	Entertainment	64	512	-	8 (Ethernet)	Digital	WIFI (optional)	8 (16)	-	HIGH	(Lightjams inc., 2018)
DALI		Domotics	16	64	150	2	Digital	Bluetooth mesh (optional)	8	1200 bit/s	HIGH	(Digital Illumination Interface Alliance, 2018)
0-10V		Domotics	1	1	-	2	Analog	N	-	-	-	(Digital Illumination Interface Alliance, 2018)
KNX		Domotics	1	57.375	1.000	2	Digital	WIFI, RF (optional)	8	4800 bit/s	LOW	(KNX Association, 2018)
MIDI	Music protocol	Entertainment	1	16	15	3	Digital	WIFI, RF (optional)	7	31,25 Kbit/s		(Hass, 2018)
Proprietary (WS2812B)		Advertisement	4.000	3	1	2	Digital	N	8	360 Kbyte/s	60	(Stoffregen, 2018), (Burgess, 2018)
Direct PWM		Universal	1	1	-	2	Analog / Digital	N	8-24	-	-	(Barr, 2001)
Z-Wave	Mesh	Domotics	1	232	30 (100)	-	Digital	Z-Wave	8	100 Kbit/s	LOW	(Administrator, 2018), (Gomez & Paradells, 2010)
Zigbee Light link	Mesh	Domotics	1	65.000	70 (400)	-	Digital	Zigbee	8	40-250 Kbit/s	LOW	(Zigbee, 2014), (Administrator, 2018)
Bluetooth	Mesh	Domotics	1	32.767 (1000+ nodes realistically)	100	-	Digital	Bluetooth Low Energy	-	1Mbit/s	LOW	(Nordic Semiconductors, 2018), (Bluetooth SIG Inc., 2018)
X-10	Uses mains net for communication	Domotics	1	256	-	2	Digital	IR, RF (optional)	1	20 bit/s	LOW	(SmartHomeUSA, 2018)

J | ViP

ViP, short for vision in product, is a context driven and interaction centered design method. Its main purpose is to help the designer develop the underlying purpose of a product, also called 'raison d'être' or the 'why', giving the product meaning or value (van Boeijen, Daalhuizen, Zijlstra, & van der Schoor, 2014). As the purpose of the ViP design method for this thesis is to find a valuable context only, a simplified implementation is used.

I.1 | Approach

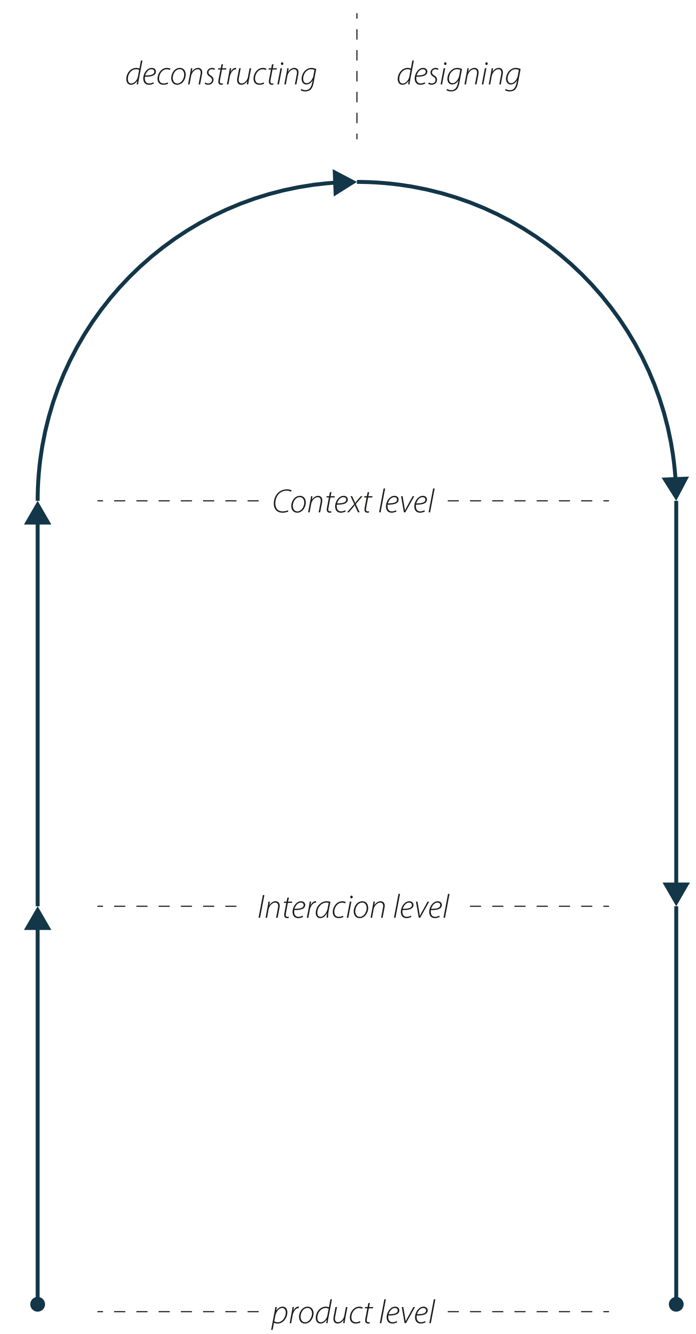
The vision in product design (ViP) consists out of two main phases (figure A). In the deconstruction phase relevant insights (factors) are gathered on data, light, the MX3D bridge, context and general topics related to this project. This forms the basis for the design phase, where the relevant insights will be cluster, and together with a future vision form a design statement.

I.2 | Deconstruction

In the preceding chapters, data, light, and the MX3D bridge were analysed not only on technical level, but also on context, function, and what they express. Figure B Figure C, and Figure D outline the main insights on these topics. A general analysis on the topics smart cities, IoT, architecture, and social behaviour in the city, was done to get a better understanding of the overall context around this project (figure E).
Presently, the social coherence in the city centre of Amsterdam is decreasing (Haanen, 2018). This is mainly due to the growing amount of tourist and inhabitants is in the old city centre of Amsterdam which create, according to recent research, one of the highest rates of nuisance in the Netherlands (Akkermans, Kloosterman, Knoops, Linden, & Moons, 2017).

Insights

Context related insights on data were gathered during the exploration on data (figure B), light (figure C), and the bridge (figure D).



ViP process

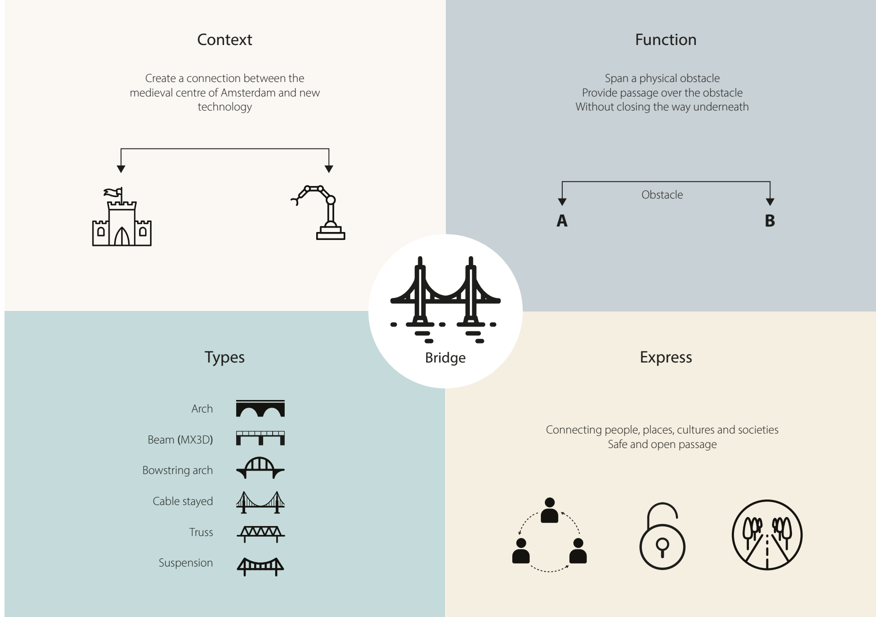


Figure B: Data insights

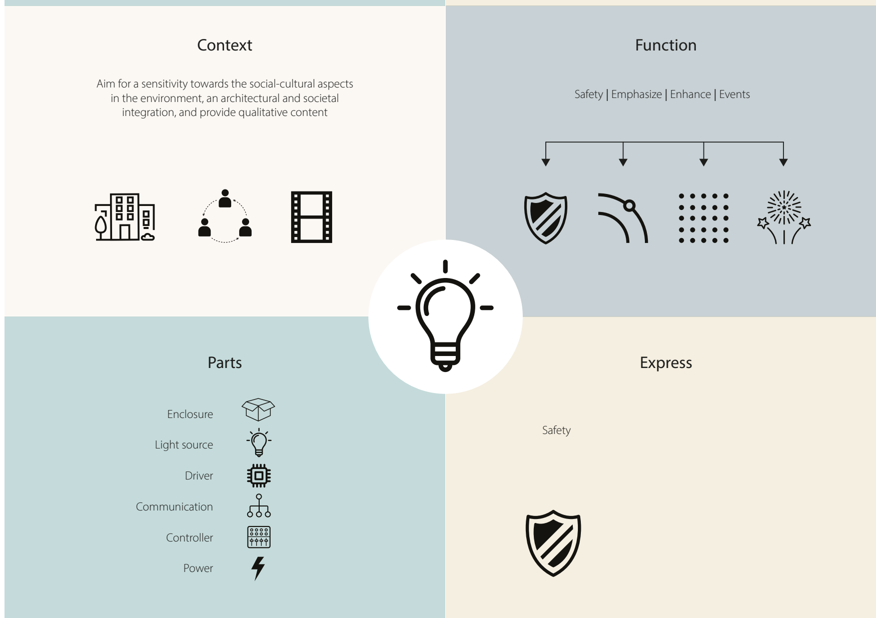


Figure C: Light insights

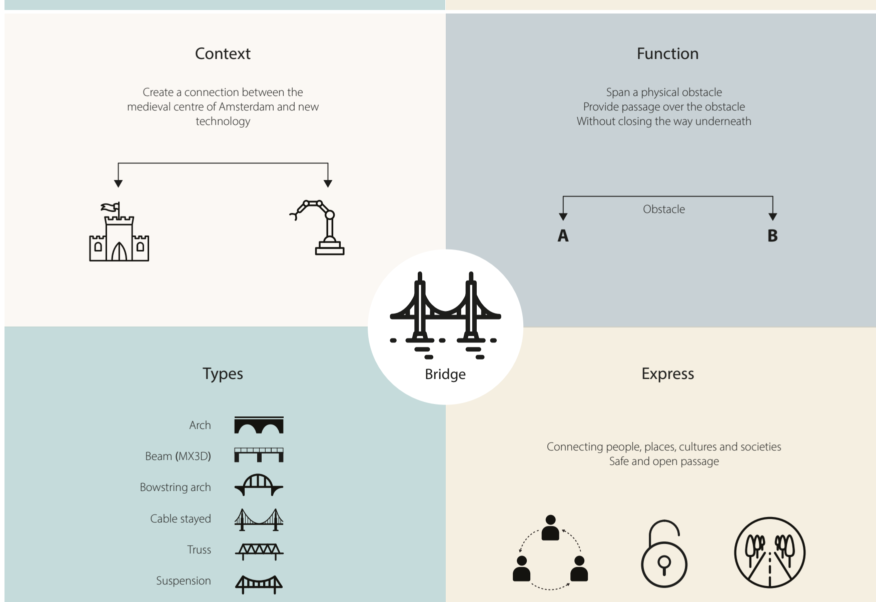


Figure D: Bridge insights

The general analysis on the topics smart cities, IoT, architecture, and social behaviour in the city, was done to get a better understanding of the context around this project (Figure E). The results were put into the factor table (Table A).

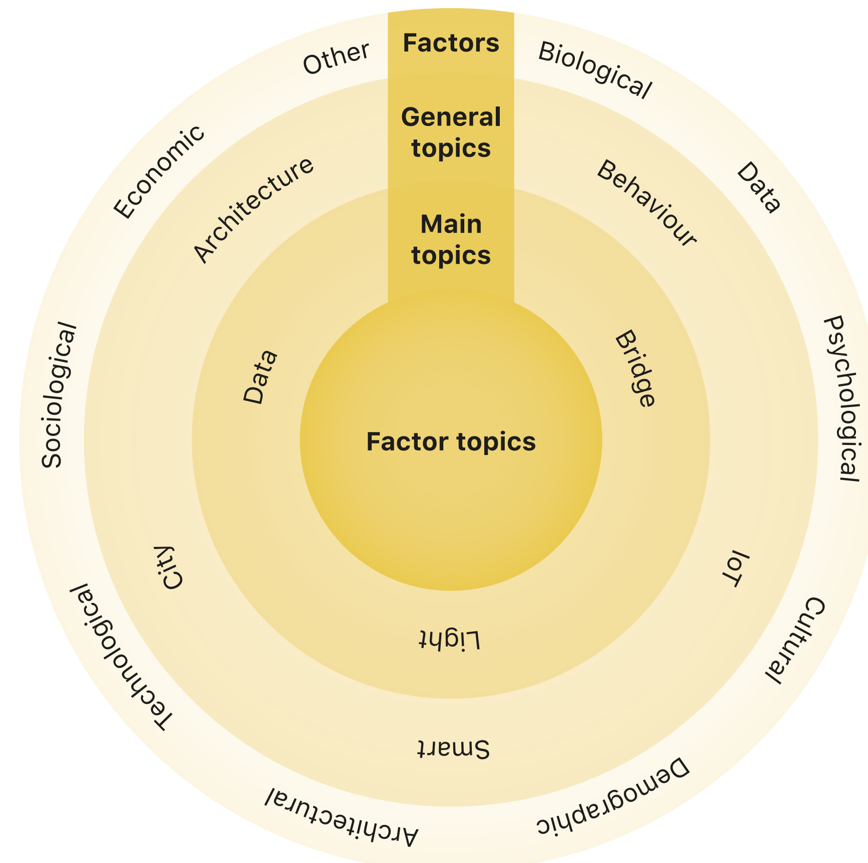


Figure E: Composition of context, insights, and factors.

Biological	Data	Psychological	Cultural	Demographic	Architectural	Light	Technological	Sociological	Economic
The human eye is most sensitive to 555 nm light in daylight, and 507 nm at night (Singer, Totzeck, & Gross, 2006)	Real time structural (health), environmental, and human data can be gathered from the MX3D bridge	Media architecture continuously profides qualitative content (Moere & Wouters, 2012)	Media architecture causes sensitivity towards the social-cultural aspects in its environment (Moere & Wouters, 2012)	The number of tourist is growing every year in Amsterdam	Media architecture aims for architectural integration (Moere & Wouters, 2012)		New technologies make it possible to equip various structures with (digital) media (Garcia, 2007)(Moere & Wouters, 2012)	Media architecture aims for societal integration (Moere & Wouters, 2012)	Media architecture is underfunded (Garcia, 2007)
Technologies change quickly, people change more slowly	Real time data from the city of Amsterdam is available (parking, traffic, environment, social...)	The MX3D bridge is build to be experienced	Joris Laarman searches for a link between tradition and new technologies	70% of the world population will live in cities by 2050 (Brown, 2014)	A bridge is a structure to span a physical obstacle without closing the way underneath to create a passage over the obstacle		Amsterdam uses smart technologies to tackle big city problems (Hendrikman, 2017)	Public data acquisition often leads to commotion (Huijbregts, 2017)	Profit from capital is higher than economic growth (Piketty, 2014)
People can not keep up with technological advancements		Humans feel unsafe in the dark	"Urban development should not be left to companies alone" (Joris Laarman, 2018, p.1)		People on a bridge see it as a normal piece of road, they are unaware of what is underneath and the bridge itself		Social media can be used to differentiate between groups of people, detect "hotspots" of people, and many other things (Mattmo, 2015)	Social coherence is decreasing in the city centre of Amsterdam (Haanen, 2018)	Data mining is big business
People only see what they need to see, or where they are working on		Humans like overview	All cultural objects will be equipped with sensors	Europe's big (smart) cities will focus on energy, (safety), and transportation ('Direction and strategy of a smart city policy.pdf', 2016)	People use a bridge as a crows nest / for sightseeing		21 Billion connected things will be in use by the year 2020 (Boorstin, 2016)	Citizens are often absent in the design of smart cities (Kupper, 2018)	Data (mining) is owned/managed by a hand full of "big payers"
		People are afraid to lose their privacy	Data (analysis) will take the need to think and do	The netherlands focus on housing, trafic, and energy ('Direction and strategy of a smart city policy.pdf', 2016)	Bridges and buildings both have a floor, hidden in plain sight		All smart objects communicate with each other	Internet of Things will evolve into a true "Community of Things" (Kowalski, 2015)	Rich are getting richer, the poor are getting poorer
		People are no owner of their own data	People are put at the sideline		Architectural surfaces are used as digital screens		All human behaviour and deeds will be recorded on any point in time and space	People move to cities because: They provide people with places to live, work, and play and the means to pursue their individual and collective goals (Moore, 2015).	
		People lose control over their life					Live is getting easier by applied technologies	Data will make products more personal (Alex, Siri, Tamagotchi)	
Developments [D]							Physical and digital become one		
Trends [T]									
States [S]				The old city centre of Amsterdam has one of the highest rates of nuisance in the Netherlands (Akkermans, Kloosterman, Knoops, Linden, & Moons, 2017)		Bridges are lit for safety			
States1 [S1]				The MX3D bridge is placed in Amsterdam's Red-light-district		Bridges are lit to emphasize architectural features			
Principles [P]						Bridges are lit to create new architectural features			
						Bridges are lit for special occasions			
						A light consists out of: Enclosure (fixture), light source, and driver			
						A lighting infrastructure consists out of: lights, power network, communication network, light controller, and media			

Table A

J.1 | Factors

Factors on all aspects of this project were gathered, clustered into subjects, and redefined (Table A). To further extract the essence of these factors, multiple people were asked to create clusters . The clusters can be defined as: common quality clusters, where all factors have more or less the same direction; and emergent quality clusters, where factors with a different topic come together and create one new topic.

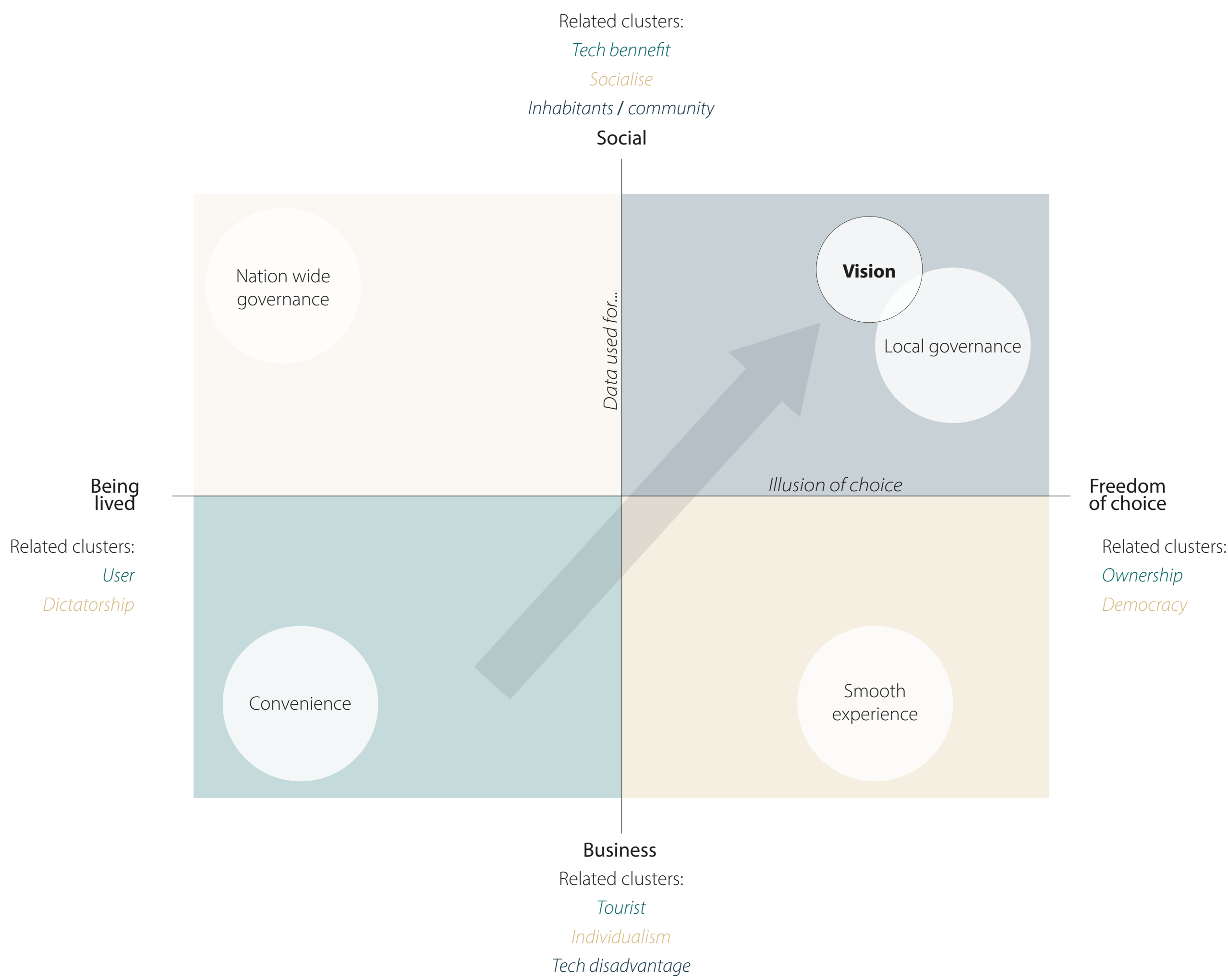


Figure F: Dimention matrix with opposing clusters.

Together, these clusters formed figure F, showing an overview on the possible future contexts of this project. The matrix has two axis which represent two important findings discovered during cluster sessions. One axis represents the feeling of freedom of choice. Do you choose what happens tomorrow? Do you own your own information/data? Does clicking “accept” in an app really feels like a choice?

While the other axis represents (the use of data for) social or business purposes. Is there more focus on the community and inhabitants, or on tourists? Is it individualistic or social?

The four quadrants each represent a cluster of factors with the same theme, and can be described as:

Convenience

- *No need for choice Live like a zombie Absorb*
- *Dormant*

Suppression

- *No power as a group or individual Central control*

Smooth experience

- *No need to worry about anything Digital butler*
- *Do what you want to do*
- *No societal integration*

Local governance

- *Transparency Involvement*
- *Control*
- *Hassle*
- *Contribution*
- *Great societal integration*

Statement direction (Arrow)

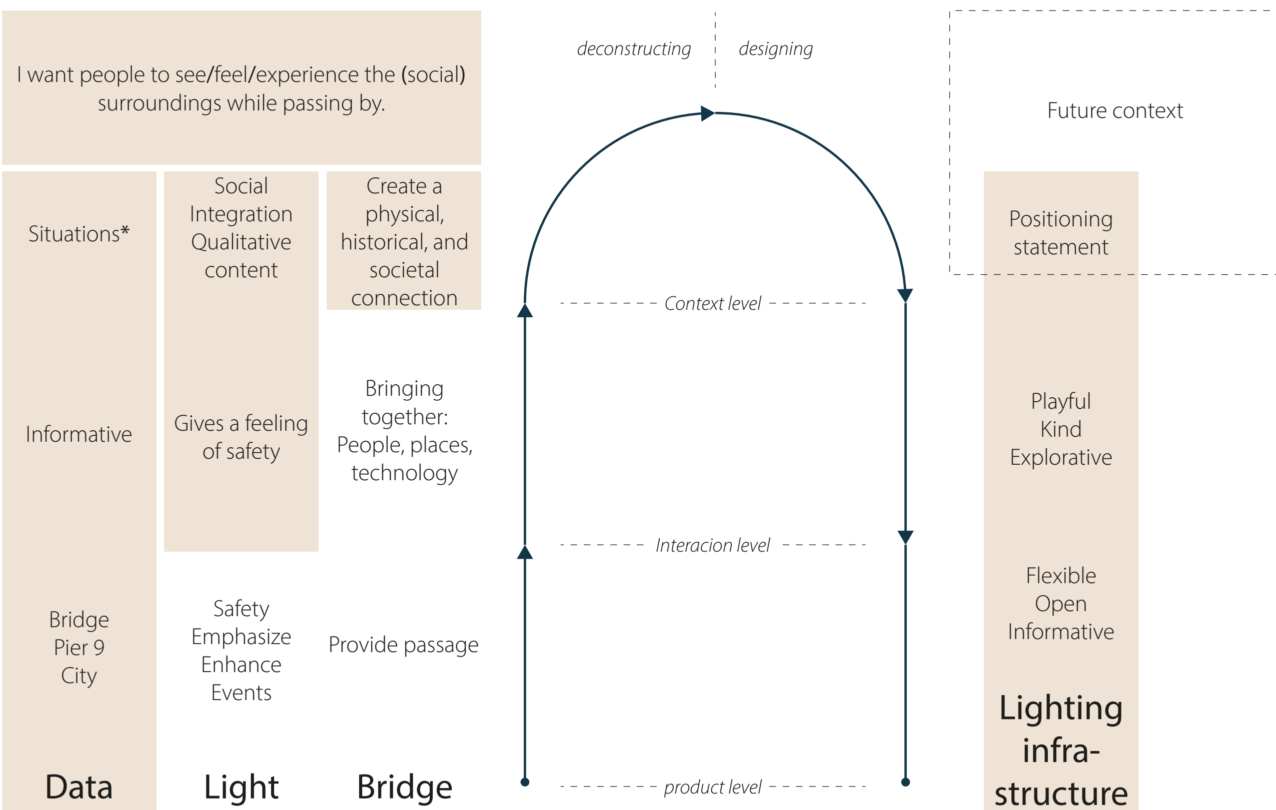
The lighting infrastructure should stimulate local governance and work as a mediator between the local society and people passing by, putting technological benefit in the hands of local society and create societal integration opposing the current situation that is oriented on business and convenience. The cluster local governance is most fitting as future direction for this project.

J.2 | Designers vision

In design, the designer always has influence on the final outcome. Personal values, beliefs, morals, and views are best made explicit according to ViP. As the designer, the statement I want to make in this project is as follows:

I want people to see / feel / experience the (social) surroundings while passing by.

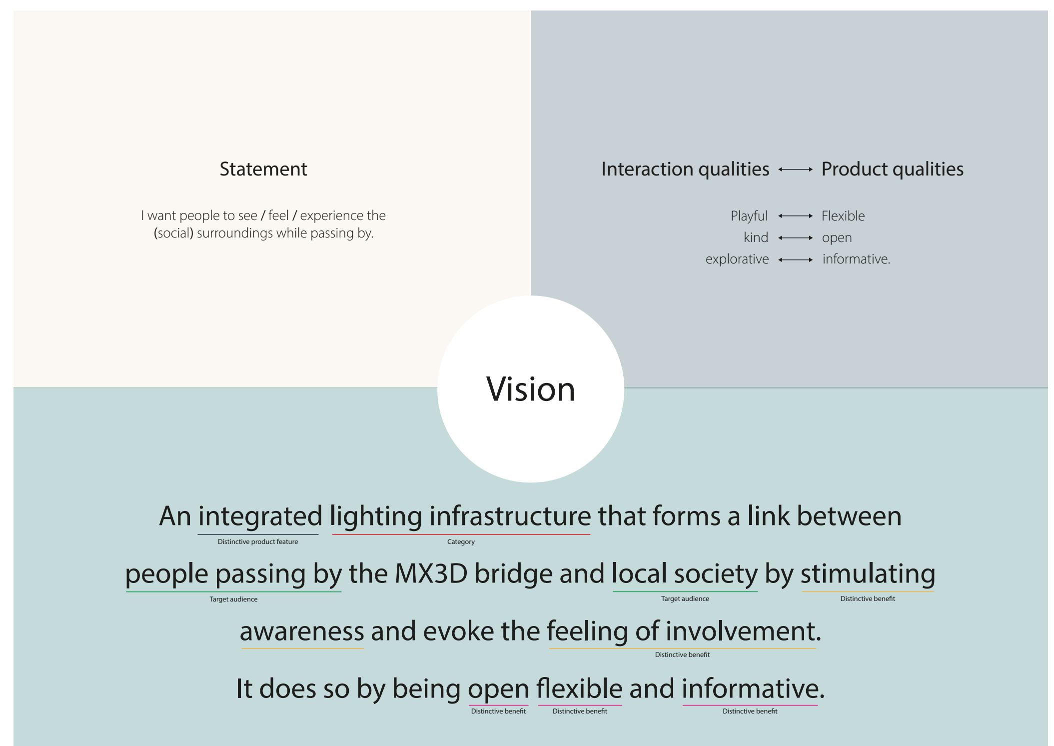
This could be interpreted as people should be more polite, less self centred, and think about people standing next of them.



J.3 | Vision

The lighting infrastructure should not only provide qualitative content by taking into account social-cultural aspects in that time and be integrated into the context it's placed in (both architectural and societal), but also create a link between the isolated people walking by and the society it is placed in. People passing by are often dormant and just absorb what they see, especially tourist. They have little to no in depth (social) interaction with their environment and just move from place A to B. This group of people has the opportunity to not only consume their surroundings and be a burden for the society they move trough, but also add value by interacting with or being aware of it. This interaction could be either physical or mental, but should create awareness, a feeling of involvement or contribution, or at least enforce mutual respect. Ultimately, it has to turn uninterested/unknowing pessants into society aware contributors.

The surrounding society of the lighting infrastructure could play a role in this by for example controlling or steering the interaction, putting the control in the hands of locals instead of a big government. This would indirectly create a link between the two groups via the bridge, and potentially enhancing social coherence between the locals.



Final vision.

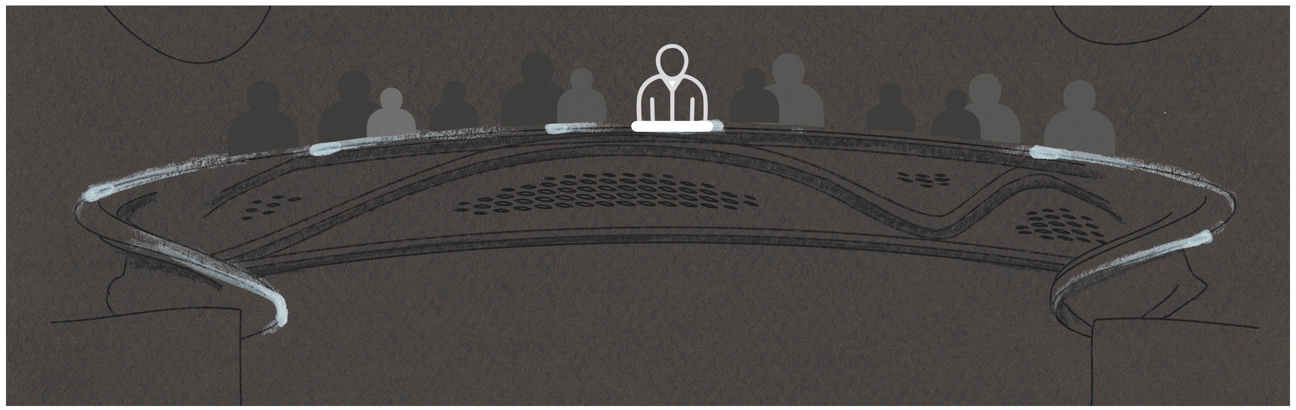
J.4 | Interaction & product qualities

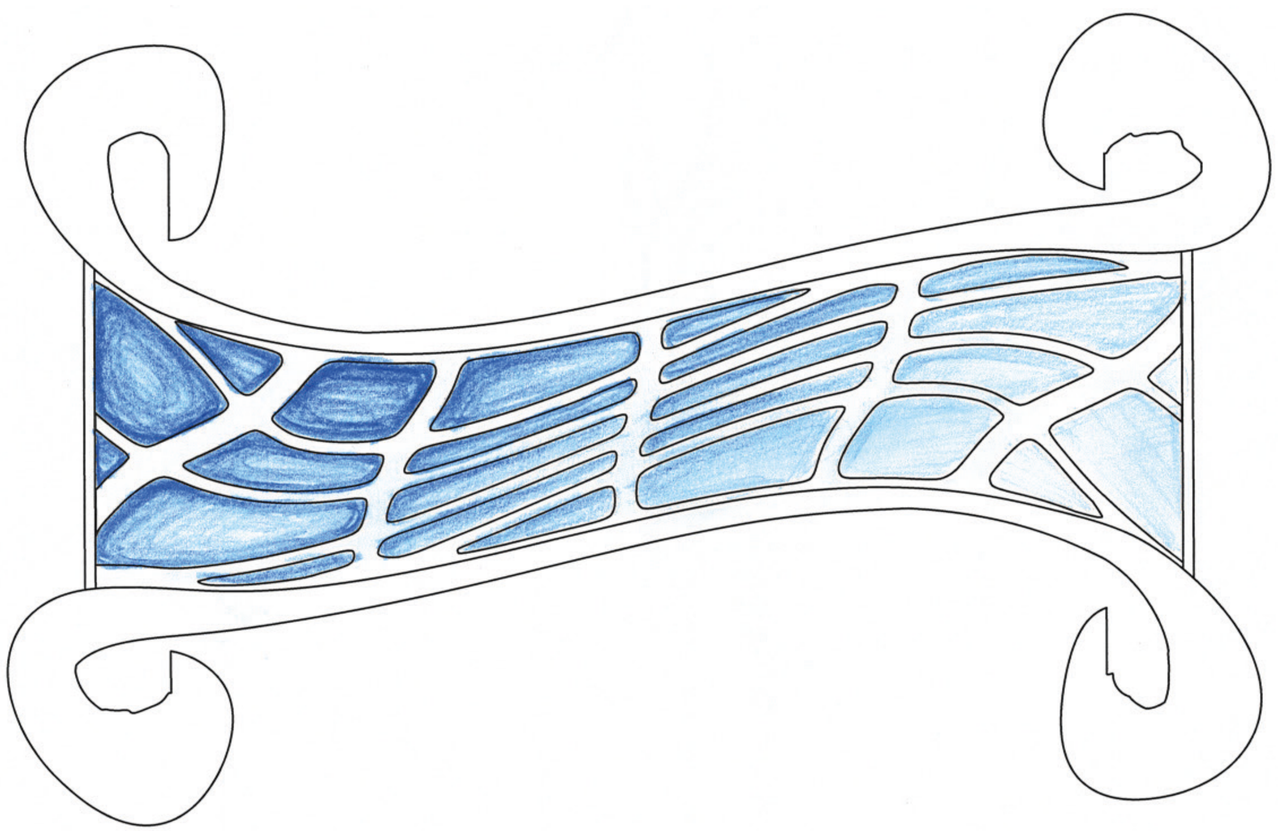
Before defining a positioning statement, the relation with the audience has to be defined. What type of interaction must the product have?
The preferred interaction could be described as walking with your dog in the park, being guided in a playful way, exploring the surroundings with a kind being.
To make the audience understand the intended interactions, the lighting infrastructure should have appropriate product qualities, translating the wanted interaction into product related qualities.
The lighting infrastructure is a touring guide, which let you explore within a boundary. It is a mediator and a stimulator, making you aware and inform you. It is Flexible, open, and informative.
Paying attention on purpose in the present moment is awareness. Increasing our awareness of each other, the people next to us, will enhance social coherence. The lighting infrastructure will evoke this feeling by informing its audience.

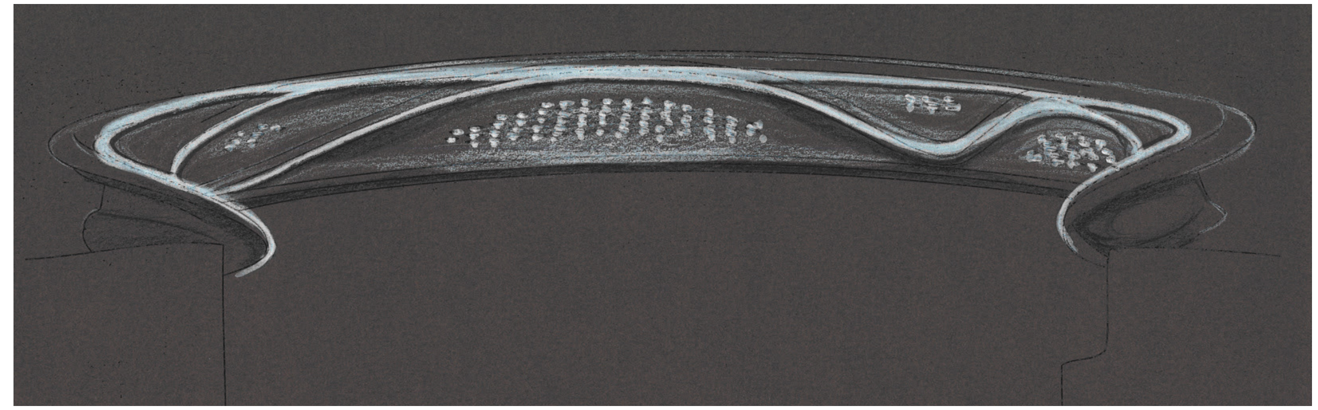
J.5 | Conclusion

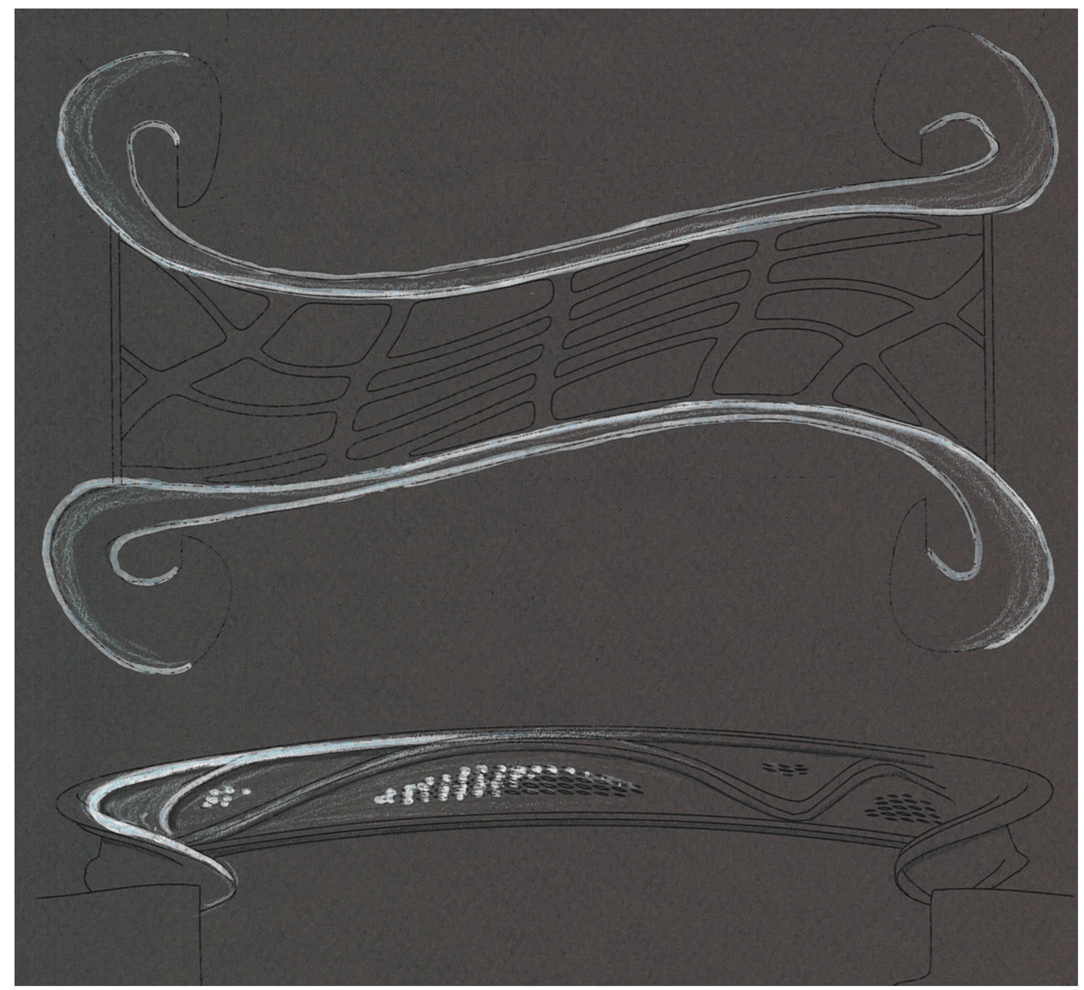
Using the ViP method resulted in a statement that is focussed on making people aware of each other, improving the social coherence, and using the lighting infrastructure to do so.

K | Sketches (impression)

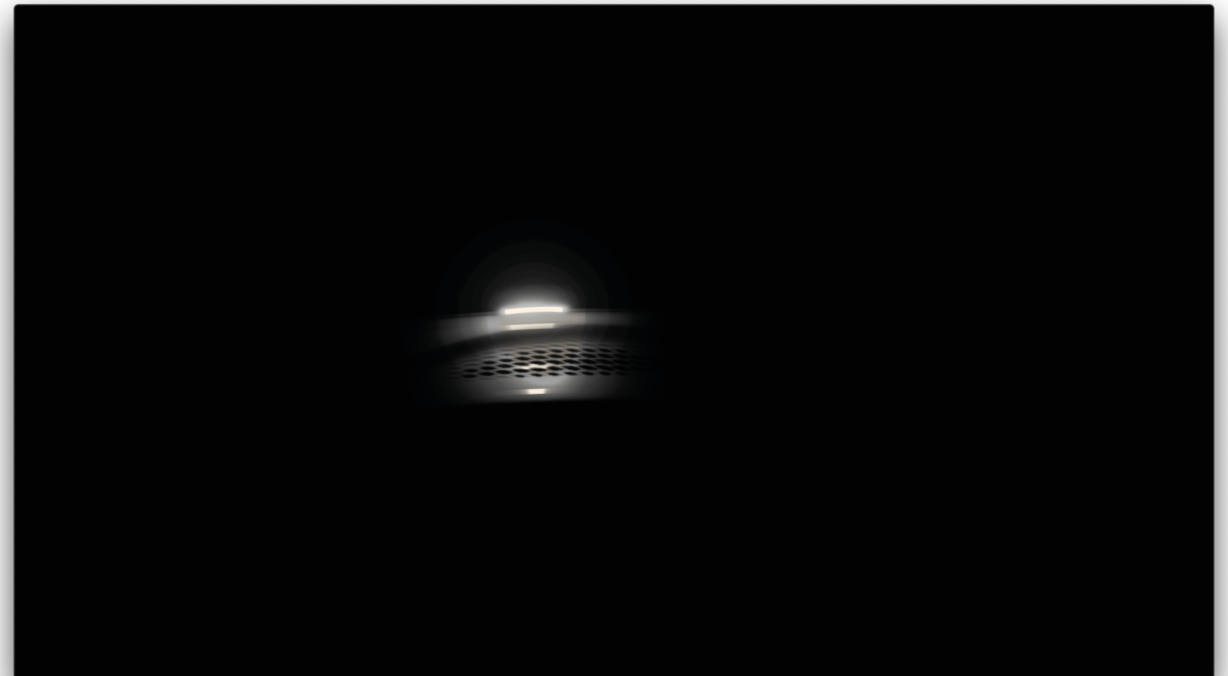




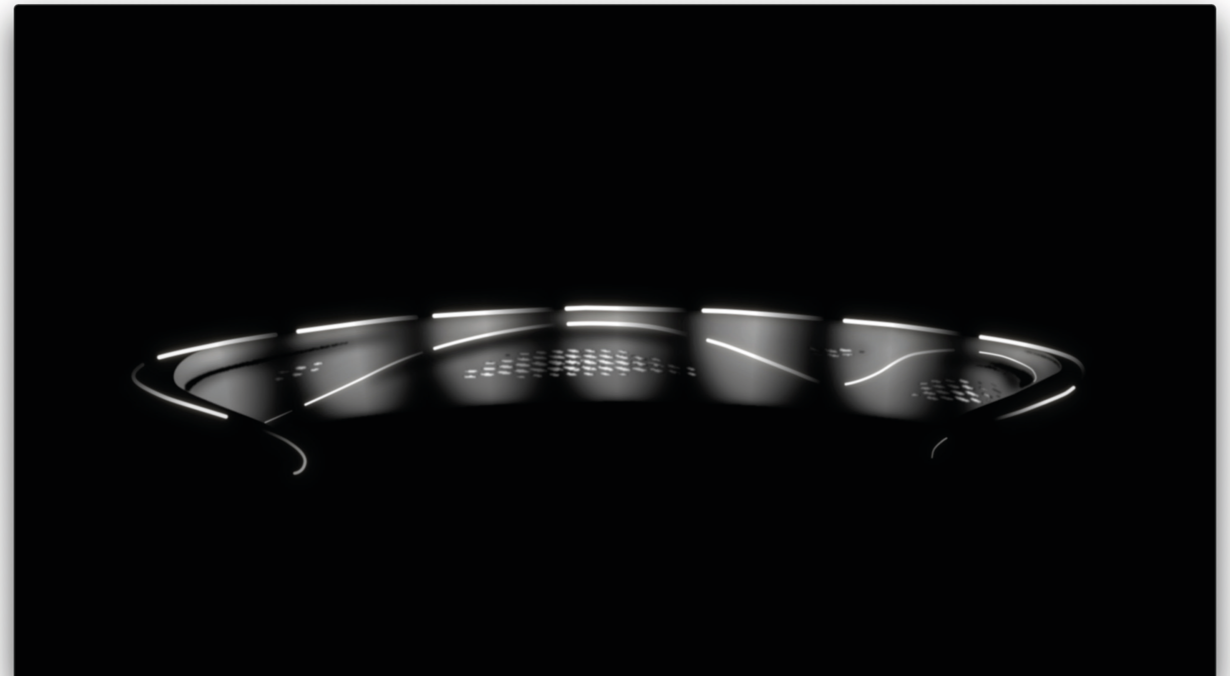




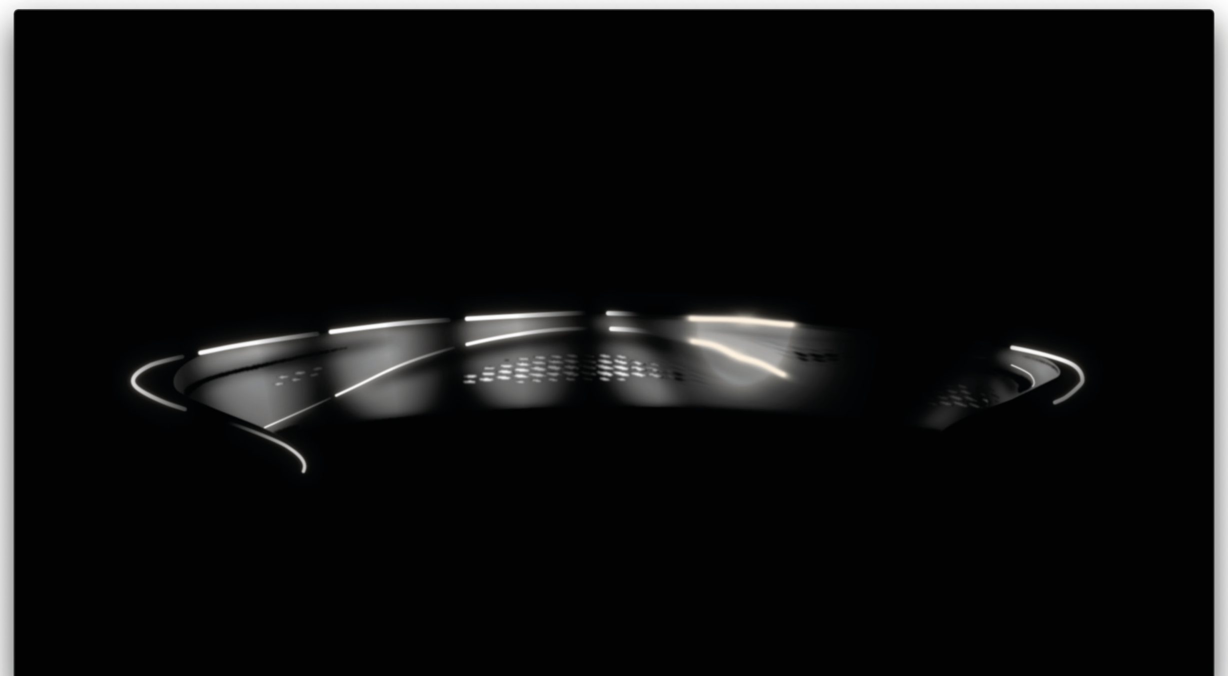
L | Animations - light only



Annoy animation.



Flow animation.



Block animation

M | User animation test - questionnair

Name: /01/19

Q1:
What is the purpose of the light on the bridge according to you, elaborate?

Animation 1:
....
....

Animation 2:
....
....

Animation 3:
....
....

Animation 4:
....
....

Animation 5:
....
....

Animation 6:
....
....

Name: /01/19

Q2a: What animation do you like most? Elaborate (why): (choose 1 per set)

Set 1
O Animation 1
O Animation 2
O Animation 3

Set 2
O Animation 4
O Animation 5
O Animation 6

....
....
....

Q2b: What animation fits best with the design of the MX3D bridge? Elaborate (why): (choose 1 per set)

Set 1
O Animation 1
O Animation 2
O Animation 3

Set 2
O Animation 4
O Animation 5
O Animation 6

....
....
....

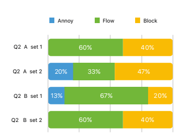
Q3: The purpose of the animations is to either elicit a feeling of movement, or annoy people on the bridge. Do you think this is correct for all animations? Elaborate on your choices (why):

....
....
....
....

N | User animation test - Results

Results

Participant	Name	Test	Date	Thought set 1 & 2 were same	Q1 - Animation 1	Q1 - Animation 2	Q1 - Animation 3	Q1 - Animation 4	Q1 - Animation 5	Q1 - Animation 6		Q2 A set 1	Q2 - A - set 1 - comments	Q2 A set 2	Q2 - A - set 2 - comments	Q2 B set 1	Q2 - B - set 1 - comments	Q2 B set 2	Q2 - B - set 2 - comments		Q3	Agrees
16	Fermin	A	di 15 jan. 2019	x	To indicate an area where people are standing still	To indicate the path walked by the person standing still	Decoration or continuous flow of people	Indicating position where I am standing still	Indicating the path I have walked until that point	Continuous flow of people or decoration		3	It does not create conflict when interacting with several people	5	It lights where I'm standing, which could be useful	2	It seems smarter since number 3 is just a continuous loop	5	Same		1: avoid people from standing still on the bridge. 2: shows the interruption in the flow of people. 3: to stimulate a continuous flow of people.	Yes
11	Mauritio	A	di 15 jan. 2019	x	If someone stands still for sometime, the light indicates his presence	One stands still so light indicates his presence and the stream of light shows the direction where the majority of people walk	Same	Light shows where I am standing	One shows my location, stream shows direction of other people	Direction of my walk direction / that of the majority of the people		2	Spotlight is less invasive than 1st one.	6	Nice to have personalised light which follows you	2	Like a blood stream on organic shape	6	More subtle, no light in my face, still like the personal light on the side of the bridge.		1st is	Half
4	Roland	A	ma 14 jan. 2019	x	Gelieve door te lopen	Bepaalt tempo door lopen (gelieve), ga om de omleiding	Loop richting en tempo	Doorlopen, komt irritant over	Waarschuwing, doorlopen	Tempo van lopen		3	Verlichting was regelmatiger	4	Voor voetgangers op de brug is dit prettiger	1	Rustgevend, komt beter tot zijn recht	6	Mooie contouren van de brug		Er blijft doorgang in de looprichting. Verlichting werkt irritant, dus het doel is blijkt, doorlopen.	Yes
3 P	Heidi	A	ma 14 jan. 2019	x	It warns that person standing too long there	Blocking or bothering other people because it blocks general light movement	Light walks together with pedestrians	I don't know, something is wrong	I'm the starting point of the light	Guide / provoke me to move forward		2	Informative and has a function	6	pretty, like to see it is following the rail	3	Smooth, emphasise organic shape of the bridge	6	Smooth, emphasise organic shape of the bridge		It can be more annoying. Eg: annoying blinks, contrast, etc. feels like it's following me	Half
2 P	Carlo	A	ma 14 jan. 2019		Je staat in de spotlight	Je ziet beweging op de brug, dit vind ik mooi, persoonlijk uitgelicht	Je ziet beweging op de brug, de brug wordt dan meer zichtbaar	Volgens mij slaat de foto camera op hol, geen goede foto's in het donker. Maak hier geen foto's	Door afbuiging wordt gevarenzetting, zichtbare treden!	Door vloeiende beweging minder zichtbaar waar leuning stopt		3	Blikvanger	5	Gevaar zetting	3	Vloeiend	5	Duid gevaar aan		Irritant is animate *Block*, zeker bij foute bezigheden of als je niet in de picture wilt staan	Half
1 P	Emil	A	ma 14 jan. 2019	x	To speed up someone who is standing still	Provide lighting for a person? Or same as 1	Directional flow of the traffic	Amsterdam light festival?	Beacon to show where you can cross the water	Same as 3		-	-	-	-	-	-	-	-		-	
15	Angles	B	di 15 jan. 2019	x	To indicate the direction / side of the bridge the people should follow in order to avoid messy circulations	To let others know that someone has stopped so it avoids people bumping into this person	Mix of *Flow* and *annoy* so indicating direction of the circulation and someone stopping on the bridge	Divide the bridge in two opposite direction	Someone stopping on that position	Same as *block*		3	Because it aligns better with the aesthetic lines of the bridge (smooth)	6	Because it is smooth and clean (minimal)	3	same	5	I like the idea, but not the way it is displayed		1st one is annoying, 2nth & 3nth are movement	Yes
12	Melle	B	di 15 jan. 2019	x	Weg wijziging (richting aanduiden)	Blijf stilstaan, er gebeurt iets bijzonders	Persoon staat al langere tijd stil en kijkt rond, brug herkent dat	Stimuleert beweging richting de kade	Highlight, kijk een om je heen	Geen idee?		3	Past het best bij de omgeving, is subtiel	4	Triggert de aandacht	3	Volg de form van de brug	5	Volg de form van de brug, triggert de aandacht		De functie is niet altijd helemaal duidelijk, maar wellicht met opzet, want misschien moet er tijdens de interactie meer nagedacht moet worden over de experience (zoals bij kunst)	Half
9	Benjamin	B	ma 14 jan. 2019	x	Loop richting, doorstroming, niet stil staan	Voorkomen dat mensen blijven staan. Ziet er grappig uit (als mensen een selfie maken)	Doorstroming + loop richting + voorkomen dat mensen blijven staan	Doorlopen, gaat te langzaam, doorstromen	lopen! Niet goed!	Tube uitknijpen, gelieve niet stil staan, doorlopen		2	Symmetry, unity, smart, funny	4	Clearly notifying	3		6	Not too extravagant, subtile		Clear, everything does what it supposed to do	Yes
6	Timo	B	ma 14 jan. 2019	x	Naar rechts lopen	de aanwezigheid van een stilstaand persoon weergeven	Een blokkade laten zien voor mensen die van links naar rechts lopen	rechts van de brug af lopen	Mijn aanwezigheid op de brug aangeven (eventueel blokkeer ik de brug)	Ik moet rechts de brug af		3	zelfde	6	zelfde	3	Mooie vloeiende lijnen die de animatie mooi laat uitkomen	6	*3e* animatie mooi laten uitkomen, het zelfde verhaal		*Flow* kan ook het effect hebben dat mensen zich uitgelicht voelen en dus juist blijven staan	Half
5	Chinese guy	B	ma 14 jan. 2019	x	There are people on the bridge, or direction	To show the part of the bridge were people stay for a moment	To show the part of the bridge were people stay for a moment	Direction	To show location	To show location		2	Highlight design and function	5	Light is softer and more functional	2	functional	5	Light is softer and more functional		No annoyance but elicit a feeling of movement	Half
14	Bas	C	di 15 jan. 2019	x	Rustig moment op de dag, trigger om niet tegen het licht in te gaan	Iets drukker moment op de dag	Stilstaande actie geregistreerd	De mogelijkheid om ofwel stil te staan of door te lopen wordt gesuggereerd / uitnodiging om stil te staan	Verzoek om door te lopen (vriendlijk)	Trigger voor extra aandacht in die richting		3	Past goed bij de vertaal van de brug (minimalistisch / simpel idee)	5	Wanneer de brug het aandachtspunt communiceert vind ik het wel cool	3	zelfde	5	Zelfde		Movement, yes, very much effective. Annoyance, no, did not recognise this.	Half
13	Studente	C	di 15 jan. 2019	x	De bedoeling is dat je van links naar rechts gaat lopen	Zelfde als *1*, maar minder duidelijk	Mensen op straat gaan kijken naar de persoon die stil staat	De brug is drukker, er zijn meerdere mensen	Volg het licht, ga er daar af	Iemand staat stil		3	Meest dynamisch	5	De 1e is schreeuwerig, de 3e te druk	3	Gaat mee met de lijnen	6	Gaat mee met de lijnen/matched de lijnen		*Annoy* is echt irriterend. *Flow* is echt een gevoel van beweging	Yes
10	Julia	C	di 15 jan. 2019	x	Simulate directional movement. The spotlight is highlighting the person standing still	Speed of light follows the speed of people walking	Light focusses on person standing still, warning them to keep moving	Highlighting the shape of the bridge	Movement in the walking direction	Warning light: annoying		3	Flowing of movement continues, the blinking light and the spotlight are disruptive.	6	The movement is continuous, calming, guiding	1	Minimal invasive for the design of the bridge	6	It follows the lines/ shape of the bridge		It is correct for all animations	Yes
8	Bill	C	ma 14 jan. 2019		The light follows/ traces the pedestrian horizontal. Movement from 1 end to the other, it gives indication for the balustrade and direction.	Higher frequency and continuity	Specific spot light on balustrade lit up for stopping pedestrian	Spot light for where the pedestrian is located, and moving light for orientation / direction	Continuity / moving light for direction	Stop / spot light for indicating there is a person standing there in the way		2	informative	5	informative	3	Empasise	6	Empasise		alles doet wat het moet doen / duidelijk	Yes
7	Nyckle	C	ma 14 jan. 2019	x	Industrial process, conveyor belt, doorstroming bevorderen?	Indicating a direction of movement, one way street ?	Alarm! When stopping. Do not stop here. Public shaming	Quiet, no push to move further, prettig	Gevoel dat ik moet moven, minder rustig	Ga hier weg, doe niet! Niet stoppen! Raak mij niet aan		2	Deze is mooi rustig, zeker als je er zelf op staat.	5	Goede combinatie van dynamisch en statisch licht	3	Vanaf een afstandje ziet deze er erg vloeiend uit	6	Past bij design		Ik denk dat ik die gevoelens wel gegrepen heb. Bij *Flow* heb ik zeker geen gevoel van annoyance. Annoyance =1, 2+3 = movement	Yes
					Block animation		Flow animation		Annoy animation			15		15		15		15			Agrees:	15
											Aantal 1 =	0	Aantal 4 =	3	Aantal 1 =	2	Aantal 4 =	0			Aantal Yes	8
											Aantal 2 =	6	Aantal 5 =	7	Aantal 2 =	3	Aantal 5 =	6			Aantal Half	7
											Aantal 3 =	9	Aantal 6 =	5	Aantal 3 =	10	Aantal 6 =	9			Aantal No	0
Annoy												0,00%		20,00%		13,33%		0,00%			Yes	53,33%
Block												40,00%		46,67%		20,00%		40,00%			Half	46,67%
Flow												60,00%		33,33%		66,67%		60,00%			No	0,00%



Key words Q1

Flow animation (quayside perspective)		Block animation (quayside perspective)		Annoy animation (quayside perspective)		Flow animation (on the bridge perspective)		Block animation (on the bridge perspective)		Annoy animation (on the bridge perspective)	
Walking direction	11	Walking direction	11	Someone is standing still	9	Walking direction	7	My location	5	Keep walking (order)	6
Walking speed	3	Someone is standing still	7	Give person on the bridge attention (Spotlight / public shaming)	5	Keep walking (order)	6	Walking direction	3	I'm standing still	4
Movement / flow of people	3	Walk this speed (order)	2	Keep walking (order)	4	Movement / flow of people	2	Keep walking (order)	2	Someone is standing still	2
Decoration	2	Someone is blocking the bridge	2	Stand still (order)	1	Walking speed	1	Indicate path	1	Extra attention towards light	2
Walking side	2	Blockage	2			Decoration	1	No idea	1	Annoying	2
Keep walking (order)	1	Walk (order)	1					I'm the starting point of the light	1	No idea / something is wrong	1
Same speed as pedestrians	1	Indicate path	1					Walk or stand still (order)	1	Look around you (order)	1
		Highlight the shape of the bridge	1					It is busier on the bridge	1		
								Highlight the shape of the bridge	1		
								No push	1		

Animation qualities	Flow	Block	Annoy
	Elicit the feeling of movement	Elicit the feeling of movement	Person standing still
	Stimulating	Stimulating	Put that person in a spotlight
	Unconsciously	Make conscious	That person is not allowed to stand there
	Animation speed adapts to average walking speed of people on the bridge	Animation speed adapts to average walking speed of people on the bridge	Chase away / repel
	Direction	Direction	Annoy that person
	Walk on the right side	Walk on the right side	Give negative attention
	Don't stand still	Don't stand still	Don't stand still
	Minimum animation speed (@@@km/h)	Minimum animation speed (@@@km/h)	Keep walking
	Keep walking	Keep walking	
		Person is stopping the flow	
		Put that person in a spotlight	
		Public shaming	
		Blockade	

O | User animation test - visuals

Start

A

This is the MX3D bridge

It is:

- 3D printed (steel)
- equipped with various sensors
- smart

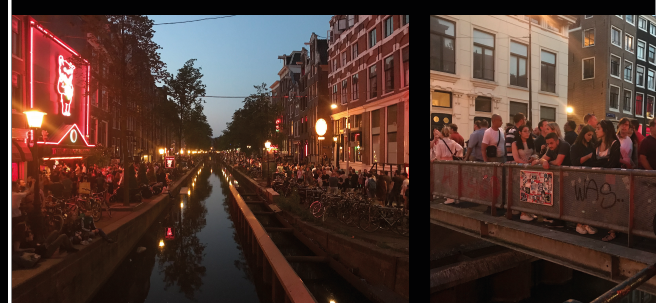
It will:

*- **sense** what is happening **on** and **around** the bridge*

- know where you are standing on the bridge

It will be installed in Amsterdam in the Red Light District:

Where it will be this crowded in the evening:



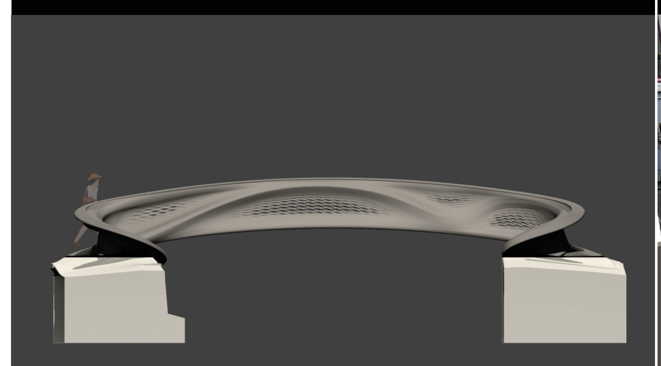
A lighting infrastructure

- will be installed on the MX3D bridge

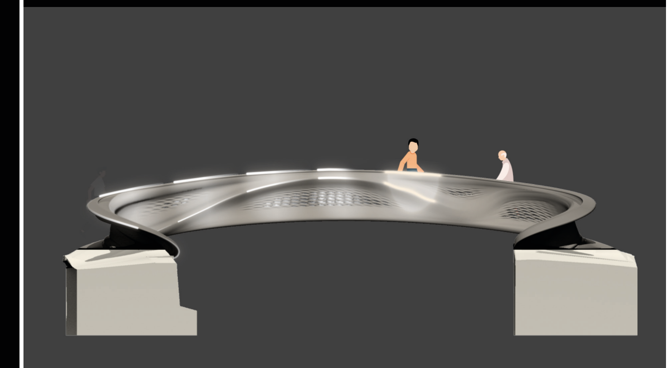
- displaying animations controlled by the smart sensors

Q1

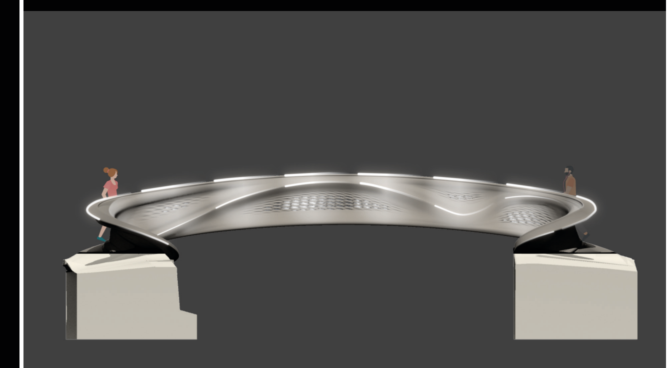
Q1 - Animation 1



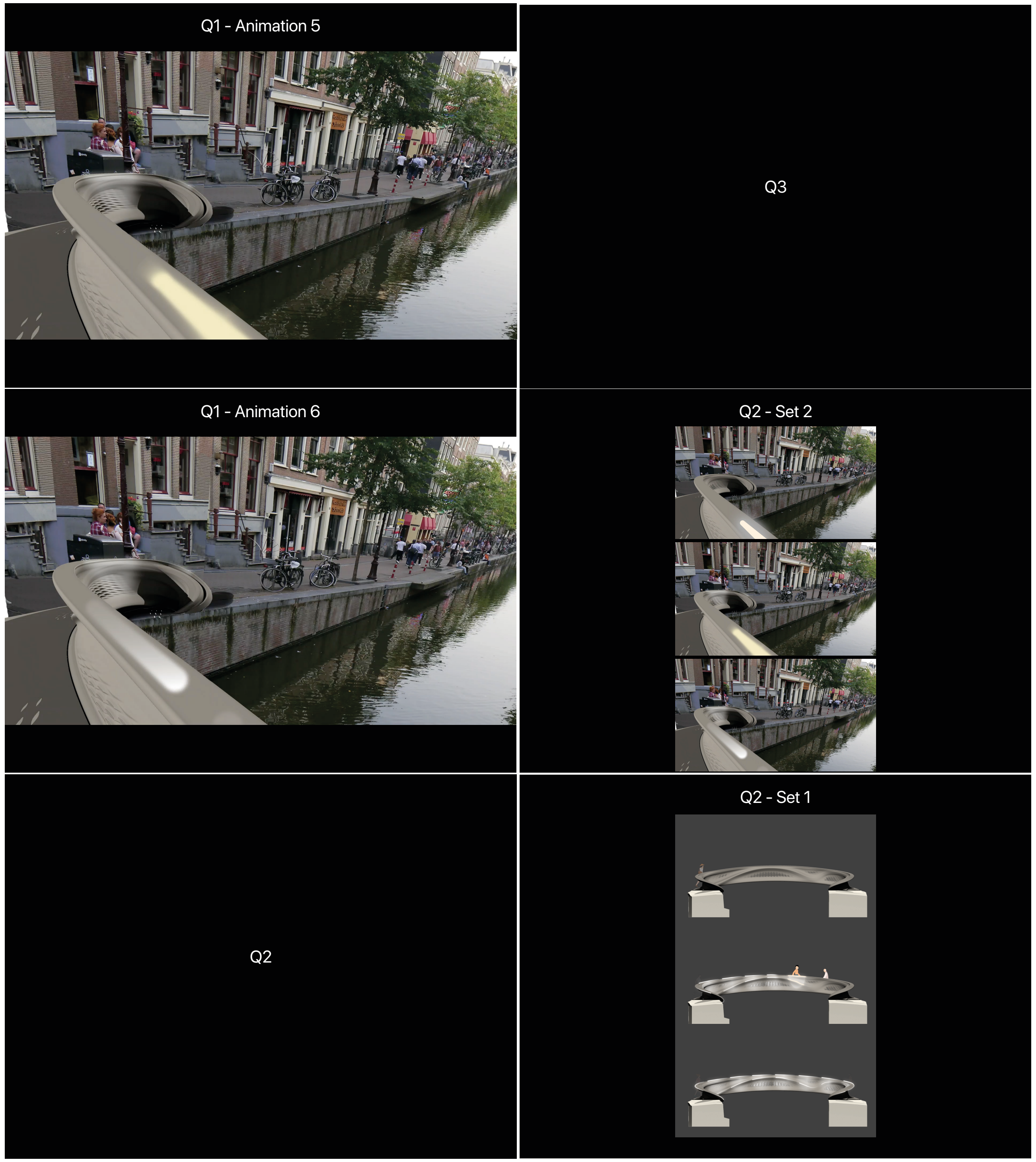
Q1 - Animation 2

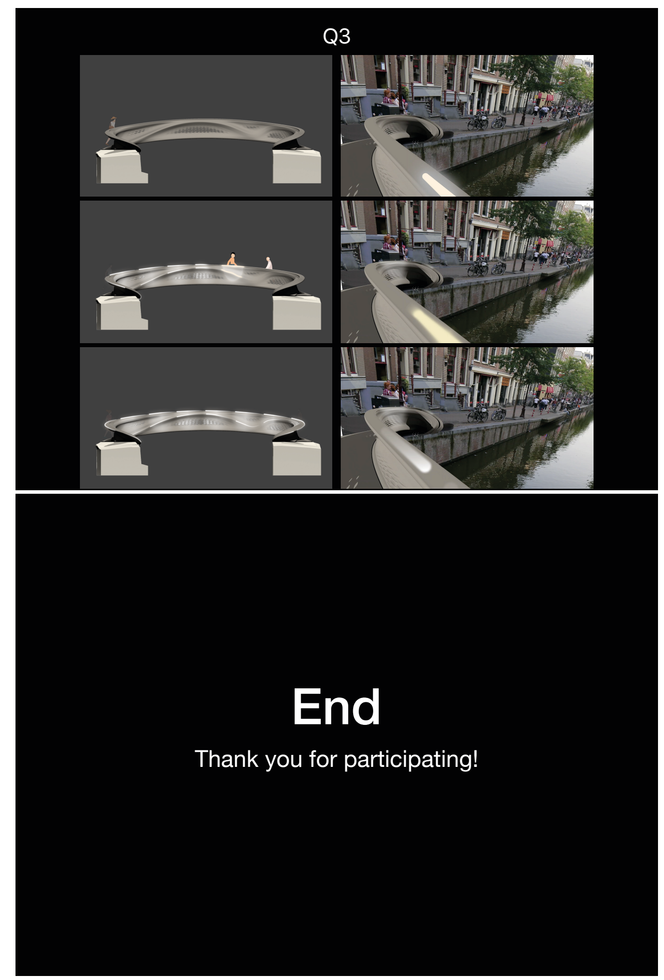


Q1 - Animation 3



Q1 - Animation 4


Q1 - Animation 5
Q3
Q1 - Animation 6
Q2 - Set 2
Q2
Q2 - Set 1


Q3
End
Thank you for participating!

P | DDW Demo code sniplet

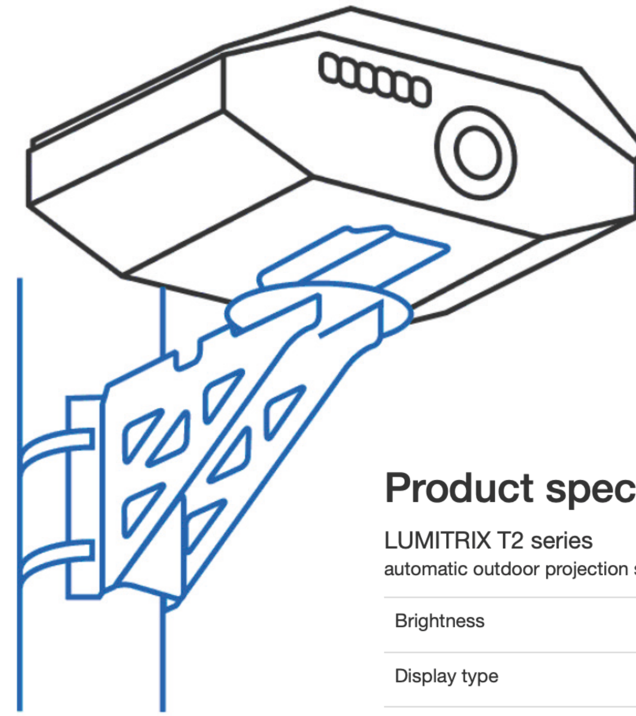
Code sniplet of JSON data retreval.

```
// Retreve data from JSON file
void retrieveData(){
 JSONObject data = loadJSONObject("data.json");
 peopleOnBridge = data.getInt("people_on_bridge");
 avgWalkingSpeed = data.getFloat("avg_walkingspeed");
 JSONArray segments = data.getJSONArray("handrail_touched");
 for(int i = 0; i < segments.size(); i++){
   activeSegments[i] = segments.getBoolean(i);
 }
 dataRequested = false;
}

// Send data to Arduino
void sendData(){
 if(firstLedValue>=256){
   firstLedValue=0;
 }
 else{
   firstLedValue++;
 }
 serialPort.write(&apos;D&apos;);
 serialPort.write(firstLedValue);
 serialPort.write(-1);
}
```

Q | Projection mapping technology

Lumitrix projector mounted on a pole, projecting text on a building.



Product specification

LUMITRIX T2 series
automatic outdoor projection system

Brightness	6.000 ANSI
Display type	DLP
Lamp life	2.500 h
Native resolution	WUXGA 1920 x 1200 or XGA 1024 x 768
Aspect ratio	16:10 or 4:3
Throw ratio (lens)	1.07 - 1.71 or 1.50 - 2.40
Zoom & focus control	motorised
Wireless control channels	GSM/2G/3G/4G, Wi-Fi
Video memory	20 GB
Ingress protection	IP43
Operational temperature	-15° C / +35° C
Audio output	2x XLR balanced audio
Dimensions	H:250 x W:675 x L:530 mm
Camera	5 Mpix (night vision)
Weight	23 kg
Power consumption	AC 230 V ~ 50 Hz / 550 W
Overvoltage protection	power supply, lan, audio
Optional accessories	wall & column attachment system

Lumitrix specs.

R | Adressable LED technology

Digital adressable LEDs encapsulated into a frosted tube protecting them from moisture and physical damage while at the same time creating a smooth transition between the LEDs.

Digital adressable LEDs that are inside the tubes, these were also used during prototyping (Adafruit, 2018).