MASTER

Potential of a wind-energy façade element . WE-Façade | Wind-Energy façade

"guidelines for application on buildings in Dutch cities" . product development of a wind-energy façade building element

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WE-Façade | Wind-Energy façade

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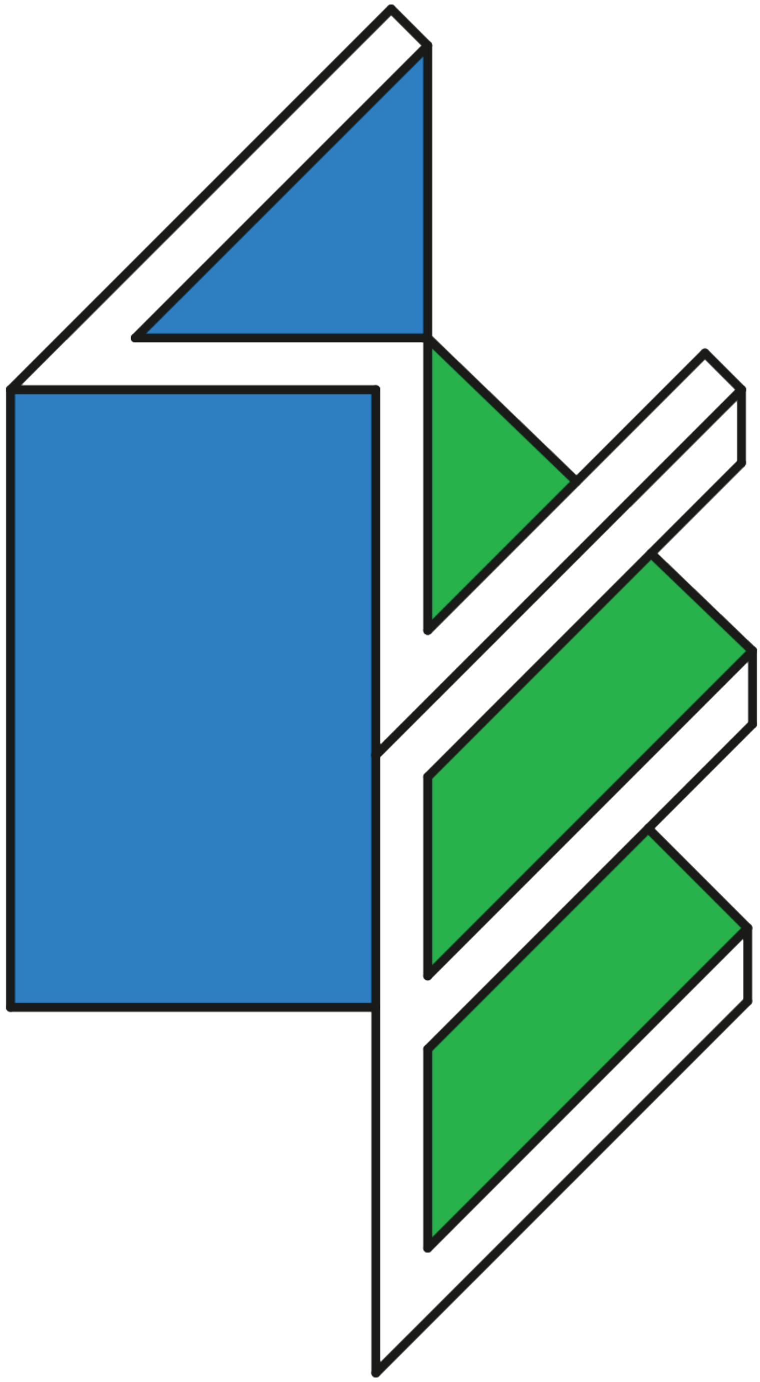

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Graduation project report
Part 2/2

Eindhoven University of Technology
Mastertrack Building Technology

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Foreword

In this report the graduation project of Yvette Eskander and partly co-student Merijn Boon within the Building Technology mastertrack at the Eindhoven University of Technology Boon on the wind-energy in the building envelope is described. Instead of following the standard procedure of graduating in a predetermined subject, the subject of this graduation project is defined by the students themselves together with prof.dr.ir. C.P.W. (Chris) Geurts. The research and product development carried out for this project were guided by three experts on the topics prof.dr.ir. C.P.W. Geurts, ir. A.J. Bronkhorst and ir. M.M. van Kins.

The graduation project consists of two phases; phase 1 the research phase and phase 2 the product development phase. The research of phase one was mostly conducted by both students together as phase 2 was mostly individual. Due to this division of the project in different phases, the reports are also divided into two separate parts. However, the content of part two is a sequence to the research of part one. This report contains the report of part two of the project, the WE-façade product development.

Part one consists of research on several topics regarding wind-behaviour, wind-flow patterns and amplifications around buildings in urban areas and wind-induced pressure distribution and differentials on building façades. Also currently available wind-turbines were evaluated. The research provided a list of design rules on three scales namely the urban scale, building scale and product scale for the design and development of the WE-façade product in phase two of the project.

Phase two which is described in this report, consists of the applied design rules in the product requirements, the design principles and concept of the product with subsequently an open field test of the concept. Finally, a proposal for the design of the product is presented, after the drawing conclusions of the open field test and adjustment of the product to the results.

I would like to thank my tutors prof.dr.ir. C.P.W. Geurts, ir. A.J. Bronkhorst and ir. M.M. van Kins for their expertise, tips, guidance and support and keeping me focussed during this graduation project. Finally, I would like to thank my fellow graduate student Merijn Boon for his great (team)work and effort.

Yvette Eskander

August, 2014

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Project description

The project description, which exemplifies the purpose and division of this project in two the two seperate phases namely the resesarch phase and the product development phase is described in this chapter. The contents of the two phases of which this project consists are shortly explained and an overview is given of the motivation, goals and problem definition of this graduation project after which the guidelines as destilled from the research of phase one are summed up for the product development of the WE-façade in this report.

1.1 Introduction

As described, the Building Technology master track graduation project consists of two consecutive phases; a research phase and a product-development phase. In this report the second phase, the product development is described. The goal of the first research phase was to determine the potential of a wind-energy façade system in Dutch cities and the Dutch climate and provide guidelines for the application of a wind-energy façade system in Dutch cities. Therefore, the result of phase 1 was to define a set of guidelines or design rules for the design and application of a wind-energy façade system. The research was conducted on several scales namely the urban scale, building scale and product scale and provided guidelines for each scale. The urban scale provides design rules for the suitability and type of urban typology, location and application height of a wind-energy façade system and the most suitable common building types. The building scale provides design rules regarding the type of buildings which are suitable for the application of a wind-energy façade system, the flow patterns and wind velocity amplifications around the building which determine the most suitable positions for the wind velocity based system and pressure differences on the façade to define the most suitable positions for a wind-energy system based on wind induced pressure differences. Small building edge modifications were also discussed on the building scale. Finally on the product scale, all available horizontal axis wind turbines (HAWT) and vertical axis turbines (VAWT) with a 3,5 m height or diameter maximum were evaluated on several parameters regarding their dimensions, average yearly yield in the Dutch climate based on wind statistics from the KNMI (2011) and costs including the return of investment period. All these research parts come together in a list of design rules and are described in paragraph 1.3 which create boundaries and provide guidance for the design of the WE-façade product.

IIn this second phase the goal is to design a wind-energy façade system which is widely applicable to the most common building shapes, square and rectangular, as found in chapter 2 of the research report by Boon and Eskander (2014) with guidance of the design guidelines. The goal for the product-development phase as stated in the WE-façade graduation plan;

"The main purpose of this graduation project is to develop a building element which is designed and developed from a building technology oriented perspective. This building element is developed to generate wind-energy on the building façade or edges of the building envelope, while preserving architectural freedom. It should be suitable for application to buildings which are relatively higher than the dominant surrounding roughness elements. The building element can be either an integrated system or a system-independent add-on. With this product we aim to increase the share of wind-energy solutions in renewable energy generation in the urban environment."

1.2 Problem definition

In this paragraph a recap of the problem definition will be described, as this is also discussed in the first part of the project. Firstly, there's a lack of small scale generic renewable energy generating solutions is available which generate wind-energy. Many types of wind-turbines exist. However, these systems are not fit or designed for implementation on a building or even in an urban environment. A few well-known examples such as the WTC building in Bahrein shown in figure 1.1 or the Pearl River Tower in Guangzhou in China shown in figure 1.2, incorporate wind-turbines in their design. However, these buildings and shapes are specifically designed to include these large scale wind-turbines and enhance the wind-turbine performance. There are no small products available which can be applied to any building without significantly altering its aesthetics, shape or concept, similar to solar-panels for example.

Figure 1.1 | WTC building in Bahrein (Atkins, 2007)

Figure 1.2 | Pearl River Tower in Guangzhou, China (Adrian Smith and Gordon Gill Architecture, 2013)

Secondly, there is a demand for generally applicable small scale products available for renewable energy. With the WE-façade product, the aim is to develop a wind-energy generating product which is suitable for the most common types of buildings in order to expand the available small scale renewable energy products for application in buildings, especially considering the 2020 EU directive. This directive states that by the year 2020 nearly all new buildings should be zero-energy buildings (EPBD, 2012). Zero-energy buildings are buildings which generate its energy demand on-site or nearby by renewable energy sources.

Thirdly, the nowadays well-known solar-energy solutions are most efficient for generating renewable energy generation during the summer months due to fluctuation of solar irradiation during the year with significantly more solar irradiation hours in summer. In the winter wind-energy solutions could complement the renewable energy generation, as explained in the graduation plan in paragraph 1.2. Wind velocities also fluctuate during the year; however wind velocity fluctuation is on the opposite trend as solar irradiation. These characteristics of both solutions ensure that solar-energy solutions and wind-energy solutions are complementary. Due to the lack of small scale generic wind-energy solutions which are suitable for buildings, these complementary characteristics remain unutilized.

For the extended problem description; the explanation and description of large scale wind-energy shaped buildings, the EU-directive and the complementary relation between solar-energy and wind-energy solutions, please refer to the WE-façade graduation plan.

1.3 Guidelines

The guidelines as described in the research report "Potential of a wind-energy façade element: guidelines for application on buildings in Dutch cities" by Boon and Eskander (2014) as distilled from the research, should be used as boundary conditions when designing a wind-energy façade system. The guidelines are split into several scales regarding the steps of implementation and the design of the system namely urban scale, building scale and product scale. The guidelines are given below. In chapter 2 the given guidelines are incorporated into the product requirements in order to properly use these during the product development and design of the WE-façade.

1.3.1 | Urban scale

1 | Urban typologies small & large cities contain the highest wind-energy potential.

2 | There's a minimum application height for wind-energy solutions which is dependent on the urban typology.

3 | The most common buildings are square or rectangular shaped.

1.3.2 | Building scale

Guidelines for wind-energy façade systems based on wind velocities

4 | Building façade parts in flow zone C are most suitable for the implementation of wind-energy façade systems on buildings.

5 | Wind-energy façade systems based on wind velocity benefit from:
- Wide(r) buildings | γ_{max} at L=1,5H
- High(er) buildings | γ_{max} at H=2,5L

6 | Turbulence intensity can be linked to amplification factors around a building. In general, the areas with higher amplification factors flow zones C have low turbulence intensities which is an advantage for the implementation of a wind-energy façade system. Flow zones B and D with low amplification factors have high turbulence intensities.

7 | Varying the wind incidence angle from 0° to 360° clockwise results in different amplification factors around the investigated building corner. In this case 0° is the perpendicular wind direction to the windward façade of the building. Best suitable wind incidence angles for wind velocity based systems:
- α=345°-15°
- α=60°-135°
- Non-suitable wind incidence angles are α=165 ° -285 °

8 | Suitable application heights are;
- Heights above application height boundary up to stagnation point at 0,75H
- Above stagnation point fast decline of γ however still γ>1 and therefore suitable

Guidelines for wind-energy façade systems based on pressure differences

9 | Building dimensions have no significant influence on wind-energy façade systems based on pressure differentials over the façade.

10 | For the highest theoretical peak yields for pressure short-circuiting, the top three solutions are: (1) roof-top combinations (only 1b;5a), (2) corner combinations, (3) front-back combinations. Generally, a high peak occurs whenever one of the openings is oriented towards the South-West to West.

11 | Considering the range of application and location possibilities, the top three solutions are: (1) corner combinations, (2) front-back combinations, (3) roof-top combinations.

12 | The ranking of solutions considering losses of potential yield by changing building orientation, starting with the smallest loss, is: (1) corner combinations (-11%), (2) front-back combinations (-28%). Roof-edge combinations show strongly mixed results (-15% to -37%).

13 | Front-back combinations have the largest angular bandwidth (240°), corner combinations and roof-top combinations have a smaller bandwidth (150°).

14 | Corner and rooftop-edge combinations are expected to be affected the most by turbulence as front-back combinations are expected to be least affected.

15 | Chamfering, corner-cuts or rounded building edge generally decrease the potential wind-energy yield due to decreasing amplification factors and decreasing pressure differentials. However, the wind-flow is deviated closer to the building.

16 | Fins on building edges and parapets are expected to slightly increase amplification factors and pressure differences which could be beneficial for the wind-energy yield potential. However, wind-flow is expected to be deviated away from the building.

1.3.3 | Product scale

17 | Choosing a wind-energy harvester is dependent on mostly interrelated parameters namely the return of investment period, energy yield, investment costs and dimensional properties.

18 | The most important parameter for choosing a wind-energy harvester is to be determined by the designer and/or investor and the willingness to invest, therefore there is no best option.

19 | Currently available HAWT turbines show more advantages towards several parameters than VAWT turbines considering the application in buildings.

20 | The best theoretical orientation for amplification based systems is 210° and for pressure based systems 270°.

21 | Without aerodynamic modifications to the building or design of the wind-energy system, systems based on velocity amplifications have a higher potential wind-energy yield than wind-induced pressure systems of approximately 5% to 23%.

1.4 Report

The following chapters of this report describe the product-development requirements and process of WE-façade. Chapter 2 includes the guidelines as determined from the research phase and the product requirements which are described from both a product development and building technology oriented perspective and describes requirement as set by the Dutch building codes in Bouwbesluit (2003/2012) as well as requirements and boundary conditions as distilled from the case building project “Teun” in Breda as received from ir. M.M. van Kins from Hurks Geveltechniek. Chapter 3 describes the concept and design principles of WE-façade. In chapter 4 the open field test is described in which three variants of the WE-façade concept are tested on a scale of 1:20. A proposal for the design of the WE-façade for implementation in “Teun” is described in chapter 5.

C2

Product requirements

This chapter describes the product requirements for the WE-façade system with incorporation of the design guidelines for the purpose, design and case data of the product. The product requirements are divided in a few categories namely; WE-facade product, market and target, application case data and the technical requirements. These requirements set certain boundaries and conditions for the design and application of the WE-façade system for example for the application location, dimensional and technical boundaries and visual expression.

2.1 WE-façade product

As explained in paragraph 1.1, there is a great potential market for the development of a wind-energy facade system especially considering the 2020 EU directive which states that by 2020 all new buildings should be zero-energy buildings. While many types of solar energy systems exist and large wind-turbine solutions, there's a lack of small scale wind-energy systems which could easily be implemented into a building design without a large impact on a building design or structure, in other words the product should not disturb a buildings' aesthetics and preserve its architectural expression. With this product the aim is to increase the share of small scale renewable energy systems suitable for the urban environment by developing a wind-energy façade system which is widely applicable to the most common building shapes in the suitable Dutch urban typologies. Wind-energy systems could in fact complement solar-energy systems implemented in to a building.

2.2 Market and target

Building type | The WE-façade should not solely be developed for a certain building type market. The wind-energy system should be suitable for application in both residential buildings and non-residential buildings.

National Dutch market | The system should be developed for application in the Dutch wind climate as the research conducted in the earlier phase is completely based on Dutch wind statistics. In case of a similar wind climate, WE-façade could also be implemented elsewhere. However, the main priority and development remains for the Dutch market. Guideline #1; the small and large Dutch cities are suitable and contain the highest energy potential for implementation of the WE-façade.

Target clients | Targets are most likely architects, engineers, real estate developers and real estate government authorities. These potential clients are the main decisive parties during the building project. The paying party is most likely to also be the approving party of a building design and thereby the included installations and renewable energy sources. As described in chapter 7.4 in the report by Boon and Eskander (2014), Rijkswaterstaat (2014) states that a ROI-period of less than five years is considered reasonable and profitable for energy-saving or renewable energy generating measures. In addition, energy saving or generating measures cannot be calculated into the rent prices in case of investments for housing projects according to OFW Woondiensten (2013) as this is set by government regulations.

2.3 Application case data

Case | "Teun", dr. Struyckenplein in Breda, The Netherlands

The case building "Teun" is part of a restructuring plan of the dr. Struyckenplein in Breda. The main goal is to transform the dr. Struyckenplein into the main central square in the neighbourhood with shops, community facilities and dwellings. The dr. Struykenstraat road across the square is also the main traffic connection from the city centre of Breda to the South-Western city district which with the dr. Struyckenplein square as a link between the two areas. The square is defined by walls of mid-rise buildings on the east (9 storeys) and west side (6 storeys). Teun is situated in between on the northern side of the square.

Figure 2.1 | Ground map Dr. Struyckenplein, Breda (Gemeente Breda, 2013)

Figure 2.2 | Impression of Dr Struyckenplein, Breda (MIX Architectuur, 2013)

Figure 2.3 | Impression of "Teun" at dr. Struyckenplein, Breda (MIX Architectuur, 2013)

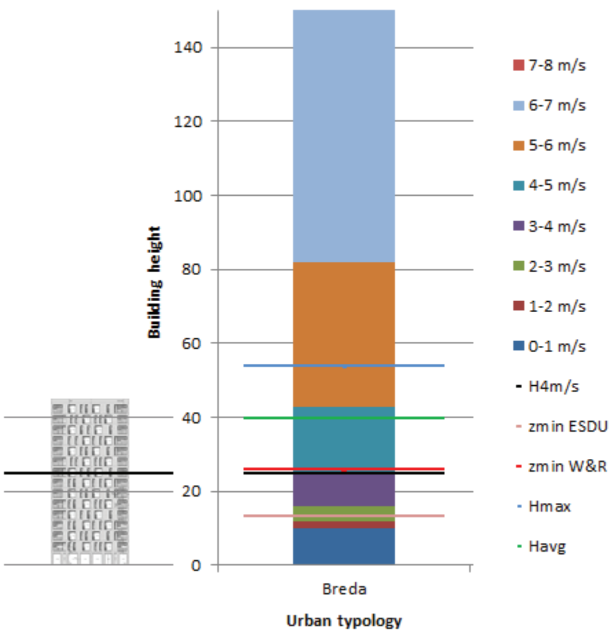
"Teun"

- Urban typology | Guideline #1 | Small city
- Building shape | Guideline #3 | Square
- Building type | Residential building
- Number of storeys | 15 storeys | 46 m total height
- Storey height | 3 m (Exception: the ground floor height is 4 m)
- Building dimensions *L:W:H* | 22,24 m * 22,24 m * 46 m ratio 1:1:2

Urban typology | Each urban typology has a different minimum application height which depends on the size of the urban typology, surrounding heights of roughness elements and average wind-velocity. As mentioned, the case for the product-development is situated in Breda which is categorized as a small city. The wind-profile for Breda is displayed in graph 2.1. For all parameters and calculations for the wind-profile see appendix A of the research report.

In Breda most buildings are low-rise buildings with a couple of mid-rise buildings. Figure 2.4 shows the location of Teun in Breda. In Figure 2.5 shows the ground map of Breda including all low-rise buildings and figure 2.6 shows the location of all mid-rise buildings in Breda. It can be concluded from these height maps that the location for the building is very advantageous considering building heights in the area around "Teun", as there are only a few mid-rise buildings and no high-rise buildings at all. "Teun" is the tallest building in the area.

- Minimum application height in Breda | Guideline #2 | 26 m
- The average roughness height in Breda | 10,8 m



Graph 2.1 | Calculated wind profile of Breda

Figure 2.4 | Ground map of Breda including the location of "Teun" (red dot)

Figure 2.5 | Ground map of Breda | Low-rise buildings only (<10 m)

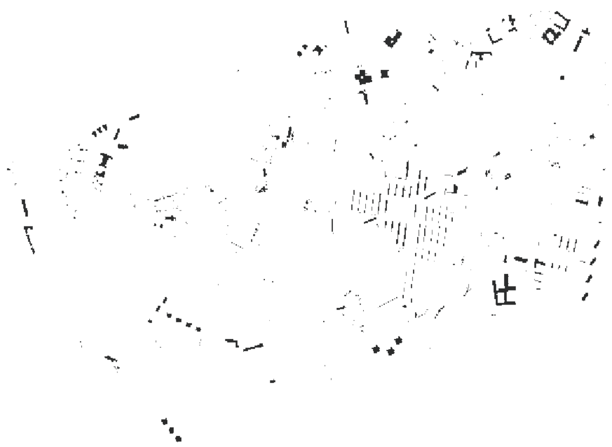


Figure 2.6 | Ground map of Breda | Mid-rise buildings only (10-30 m)

Building typology | As concluded from chapter 2 in the research report by Boon and Eskander (2014), the most common suitable buildings for development and application of the WE-façade are square and rectangular high-rise buildings. High-rise buildings include all buildings higher than 30 m, however as mentioned above the minimum application height is dependent on the urban typology. Teun is a high-rise square building with a minimum application height of 26 m in Breda.

Location in/on building | The WE-façade system should be developed and implemented in or on a building corner, see guidelines #4-16, for both systems based on wind-induced pressure differences and wind-flow amplification patterns. The most suitable orientation would be South-West to West for the building corner as derived from the research. The most suitable locations for the implementation of a wind-energy façade system are also discussed in the guidelines in chapter 1. From an organizational point of view, the choice was made to further elaborate a WE-façade system on the building corner (blue locations shown in figure 2.4) regardless of system type while Merijn Boon elaborates a WE-façade system on the rooftop edge (red locations in figure 2.4).

These locations both have their advantages and disadvantages. For corner systems based on pressure, a small recapitulation is given of the pros and cons as concluded from the research by Boon and Eskander (2014) in chapter 4.8;

+ Above average peak at stagnation height

+ Large range of other applicable locations (various heights)

+ Low sensitivity to building-orientation, high amount of application locations

+ Relatively low turbulence intensities expected, depending on the outlets location

± Average angular bandwidth, moderate sensitivity to annual variety in wind rose

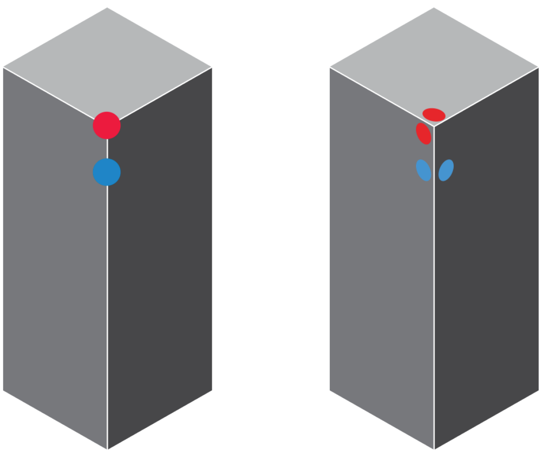


Figure 2.7 | Locations for elaboration of WE-façade, left figure is the location on the building (based on wind-flow amplifications) and right figure is the location in the building (based on pressure differences)

± Depending on presence of dominant wind direction (+ or -?)

- No unambiguous answer for yield at rooftop height

- Relying on presence of dominant wind direction

For systems based on wind velocity and amplifications guidelines #4 to 8 and #15-16 apply while for wind induced pressure systems guidelines # 9 to 14 and #15-16 apply.

System specific orientation | Guideline #20 | For a wind velocity and amplifications based system the best orientation should be 270° while for a pressure based system the best orientation should be 210°. These directions are based on wind directions with 0° being north and moving clockwise.

2.4 Product design

Building element | The WE-façade should be a ready to install prefabricated building element.

• Prefabricated elements ease the instalment process to the building and reduce the instalment period.

• With less working hours for instalment, overall costs are reduced.

• When installing WE-façade to an existing building, neighbours and potential occupants are less disturbed by the process with a prefabricated building element.

Product dimensions | The WE-façade system should maximum be 1-storey tall. For “Teun” in Breda 1 storey is 3 m. There are no maximum dimensional requirements regarding the length or depth of the system as for each building case these boundaries are different. However, instalment of the system should not require any changes to the load bearing structure. In the case of Teun, the façade is part of the main load bearing structure. Therefore, the open façade parts should be used as dimensional boundaries. The structure of Teun will be described further in paragraph 2.5.

Visual expression | The WE-façade system should follow the given architectural expression of the building which the system would be implemented to. It should fit within the building design, façade lining and materialistic expression. However, it does not necessarily have to be in line with the façade. WE-façade should not be visually imposing and should not need major design changes to the main design of the building on which the system will be implemented nor the system itself.

In case of Teun, this means that staying within the dimensional boundaries as defined by the open and closed parts of the façade in case of a pressure based system. The most often occurring open part of the façade near the South-West oriented building corner is the given normative dimensions in case of a wind-energy system based on pressure differences. This is shown in figure 2.5. For systems based on wind velocity and amplifications these visual expression issues are less clear and should be judged during the design of the system.

(Note: The outlined openings in figure 2.5 only refer to the size of the openings, not to the actual implementation building storeys for the system)

System type | The building element should be a system independent add-on. This independency is of importance as the system should be widely applicable and interchangeable with minimal design changes such as small changes in dimension, different attachment detailing and materialization when implemented to a building.

Wind-turbine | Guidelines # 17-21 | Usable wind-turbines for the WE-façade system are given in chapter 7 of the research by Boon and Eskander (2014). However, considering (future) developments of wind-turbines, it is not unlikely that in the future other or newly developed wind-turbines could perform as well or better than the given currently available turbines.

Maintenance | WE-façade including the wind-turbine should be accessible for maintenance and potential repairs in case of damage.

2.5 Technical requirements

Structure | The WE-façade building element should not require any changes of the main load bearing structure of the building before implementation. Figure 2.6 shows the load bearing structure of Teun. The main structure consists of a stable elevator core and load bearing façade elements which consists of linear wall elements and columns on the building corners. Structural loads | In case of "Teun" in Breda, requirements from the Dutch building code Bouwbesluit (2012) for structural loads and concrete floors are;

- Occupation category | Gebruiksklasse A | Area for living and domestic use
- Variable living area floor loads | qk=1,75 kN/m² | 178,45 kg/m²
- Concentrated living area floor loads | Qk=3 kN | 305,91 kg
- Variable balcony floor loads | qk=2,5 kN/m² | 254,93 kg/m²
- Concentrated balcony floor loads | Qk=4 kN | 407,89 kg

Lightweight | In order for the WE-façade to fit in within any building construction and building type, the product should be lightweight. With a lightweight product, the main structure of the building is less likely to be unsuitable for implementation. This increases the opportunities for implementation of the WE-façade product in new and older existing buildings without necessary changes to the main load bearing structure of the building.

Figure 2.8 | Normative façade openings in case of a pressure-differences based system

Figure 2.9 | Teun load bearing structure| Floor plan view

Acoustics | The occupants' acoustic comfort should be guaranteed after instalment of the WE-façade. Requirements for acoustics according to Dutch building codes Bouwbesluit (2003) are, assuming 40 dB background noises (average according to Bouwbesluit (2003)):

• Partition walls require a minimum of 20 dB soundproofing

• A bedroom has a maximum sound levels are 35 dB + 20 dB soundproofing = 55 dB overall at night

• For offices the maximum sound levels are 60 dB

Additional | It is of course of great importance that beside the above mentioned technical requirements the thermal comfort, waterproofing and damping of structural vibrations are technical issues that need to be taken into account when designing the WE-façade system to guarantee the occupants comfort.

C3

Concept

The concept of the WE-façade building product is described in this chapter. The choice for a type of system, based on wind-flow patterns or wind-induced pressure differentials proposes certain design limitations and important design principles for the product which are explained in this chapter. The design principles and choices are exemplified separately, after which the conceptual design of the product is presented with its advantages and possible disadvantages. Finally, also the choice for the type of wind-turbine is explained.

3.1 Type of system

For the WE-façade, a wind-induced-pressure based system was chosen for further elaboration after the first round of brainstorming for concepts and product designs. Wind-induced pressure systems are driven by pressure differentials over a building façade, due to pressure differences, wind-flows from high pressure areas to low(er) pressure areas. In phase one chapter 4 it is determined that pressure differentials are the highest between the wind-ward and side-ward façade and between the wind-ward façade and roof. The choice for a wind-induced-pressure system is based on several reasons. Firstly, pressure based systems are less visually imposing than wind-flow amplification based systems. Pressure based systems are more likely to be concealed inside the building as opposed to wind-flow amplification based systems which are installed outside of the building in order to use the accelerated wind-flows in the corner streams around the building corners. As mentioned before, wind-induced-pressure systems will connect a high pressure area with a low pressure area by a duct which causes wind to flow through the duct. This type of system is most likely to partly or completely be hidden inside the building. Considering this characteristic and the product requirements regarding the visual expression and product design, pressure based systems fit better within the product requirements.

Secondly, WE-façade is ought to be a generic product, which can be installed on any building without doubts from architects or other designers regarding a negative visual impact on “their” building which also supports the first argument as described before. Beside investors, architects have a high impact on the renewable energy sources or other installations which are included into a building. Therefore WE-façade should be easily implemented into a building design and easily fit the designers ideas and concept regarding the visual expression or image of the building and sustainability.

Thirdly, with a ducted turbine, the turbine could partly be protected from turbulence extremes caused by the building (Grant et al., 2008), while a wind-turbine outside the building and its potential energy yield could be strongly affected by these turbulence extremes. However, as Grant et al. (2008) describe, this advantage could come with the expense of higher sensitivity to wind directions. In other words, the range of usable wind incidence angles in order to generate wind-energy could be reduced. Sensitivity to wind directions could partly be solved with certain design choices regarding the shape of the inlet of the duct and the shape of the duct itself for example, which are further discussed in paragraph 3.2. However, this disadvantage of wind direction sensitivity also applies to systems outside of the building based on wind-flow amplifications. In addition these systems have a higher sensitivity to wind-flow patterns which is influences by the wind incidence angles which influence its performance. Pressure-differentials based systems are not as significantly influenced by wind-flow patterns as these systems are mostly driven by the pressure differences over the connected façades; the wind incidence angle is a less important factor.

3.2 Design principles

A wind-energy system based on pressure is a system which connects wind induced pressure differences over the façades of a building by a duct. By connecting a wind-induced high pressure façade area with a low pressure façade area caused by wind-flow patterns with a duct, the pressure difference drives the air flow through the duct (Grant et al., 2008). The pressure differences over the building are dependent on wind velocity and wind incidence angle. As mentioned in the guidelines, all research results are based on ducts without any aerodynamic modifications to enhance wind velocities, reduce turbulence or wind-flow interference regarding flow direction and lamination. However, even without aerodynamic modifications to the duct, the research results in chapter 4 of the research show a great wind-energy generation potential for several types of ducted wind-turbines on building corners. The disadvantage of ducted turbines as opposed to wind velocity driven turbines outside of the building is the lower energy yield which varies from 20% to 25%. In this paragraph aerodynamic modifications of the duct are discussed which could improve the wind-flow through the duct, increasing the wind velocity and thereby increase the potential wind-energy yield of a ducted turbine.

As many research results show, the building shape has a great influence on the wind-flow patterns around a building. In addition to building dimensions and small corner shape modifications, also the shape of the duct and duct inlet has a great influence on the wind-flow through and around it. The wind-flow in and around the WE-façade system is defined as non-confined flow or open flow according to Blocken et al. (2011). For non-confined flows such in the case of the WE-façade and the Ventec roof as studied by Blocken et al. (2011) as shown in figure 3.1, it is important to create a balance between the Venturi-effect and the wind-blocking-effect.

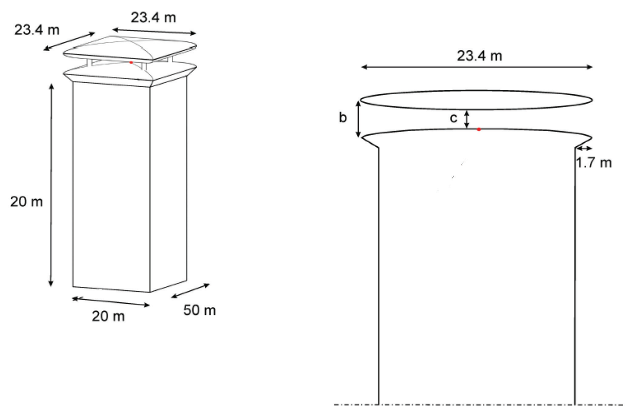


Figure 3.1 | Ventec roof (Blocken et al., 2011)

The Venturi-effect is described as an increase of the wind velocity due to a decrease in the cross section of the flow. For this description the Venturi-effect is also used as term for non-confined flows while the Venturi-effect is initially mostly valid for confined flows and should be used carefully in the case of non-confined flows as described by Blocken et al (2011). Governing the Venturi-effect in a duct would translate into a duct with a certain contraction towards the wind-turbine in order to accelerate the wind-velocity in the duct compared to the wind velocity at the inlet of the duct. However, with decreasing the duct cross section the resistance of the duct increases, causing the wind-flow to be forced around the system instead of through it. This is an explicit characteristic of what Blocken et al. (2011) refers to as the wind-blocking effect. The study by Blocken et al. investigates the optimum contraction ratio for the Ventec roof shown in figure 3.1. The results show that the negative pressure in the roof does not equally decrease with increasing the contraction height of the system and an optimum contraction height does exist. This optimum contraction height does not automatically translate into the best aerodynamic performance due to the wind-blocking effect. Therefore, testing the WE-façade concept in order to determine the influence of the contraction of the duct on the amplification in the duct and thereby the potential energy yield could provide valuable data for the search for the optimum contraction in reference to the inlet dimensions.

Not only a certain contraction is important, the shape of the inlet of the duct is also of great importance. Stankovic et al. (2009) have described the effect of a concentrator shaped duct around the wind-turbines in the WEB Project. This building is shaped as four aerodynamic teardrop-shaped building parts placed in a cross-shaped floor-plan as illustrated in figure 3.2 and 3.3. Three HAWT wind-turbines are placed in the centre of the configuration, above each other with the wind concentrator ducts around them. Wind tunnel studies and CFD studies have proved that the aerodynamically shaped inlets around the wind-turbines installed enhance the energy performance of the wind-turbines. The aerodynamic shape of the inlets curve and straighten the flow through the duct towards the wind-turbine. This also enhances the energy performance of the wind-turbines for other wind incidence angles. For example, a 45° wind incidence angle was found to be the optimum angle instead of the expected 0° perpendicular to the wind-turbine rotation direction. Needless to say, in this case the aerodynamic shape and position of the building itself compared to the orientation of the turbines greatly contributes to the optimum angle being 45°.

The Castle House building in London, United Kingdom, was also investigated using CFD simulations by Stankovic et al. (2009). The building was designed with a shroud on top of the building with three HAWT wind-turbines installed. The original design featured a shroud with no aerodynamic modifications to the shroud around three wind-turbines with a diameter of 9 m. The CFD results showed that the

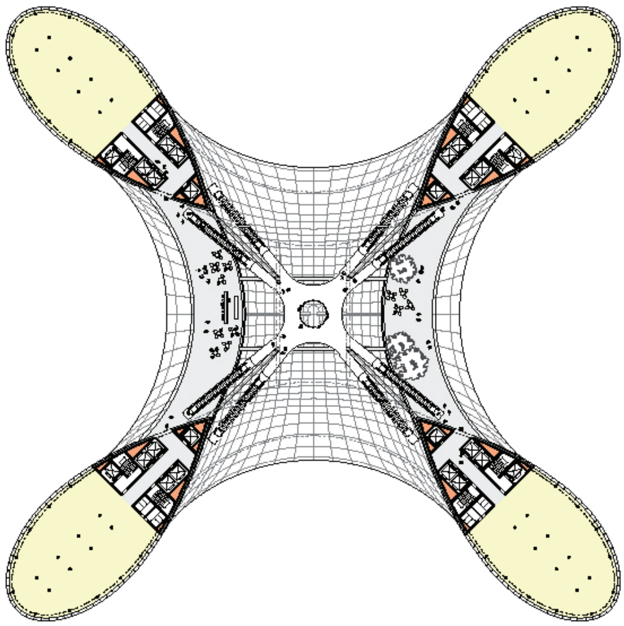


Figure 3.2 | WEB project | Elevation view (Stankovic et al., 2009)

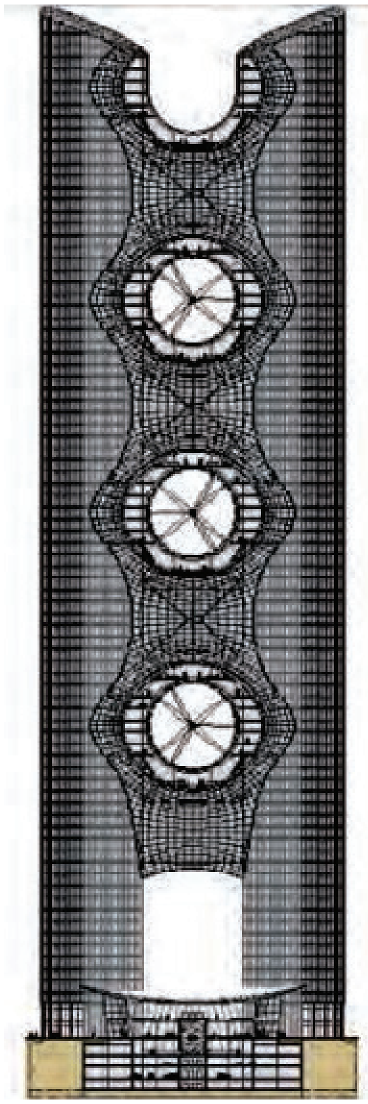


Figure 3.3 | WEB project | Floor plan view (Stankovic et al., 2009)

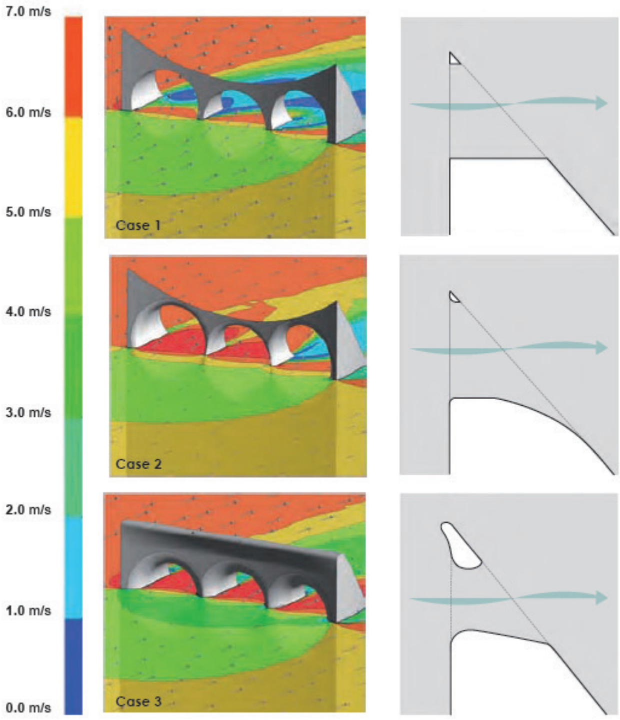


Figure 3.4 | CFD models for three models of the Castle House shrouds | Axonometric views and sections (Stankovic et al., 2009)

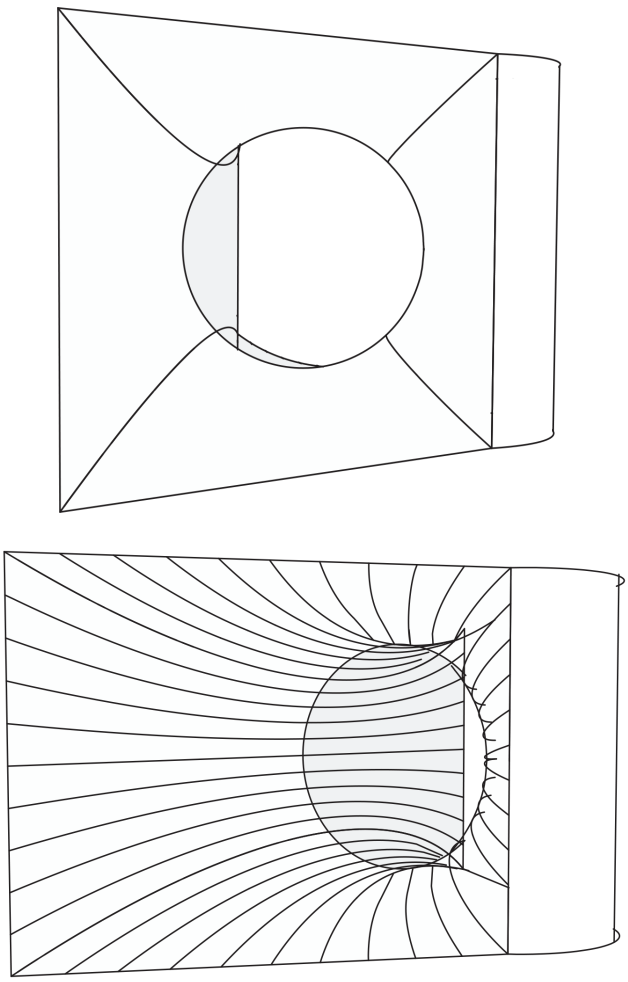


Figure 3.5 | Conceptual preliminary design

wind-turbines produced less than if these wind-turbines would have been installed in an open field. The second design featured a shroud with three wind-turbines with the same dimensions as the original design. The shroud was slightly altered and given a small fillet around the wind-turbines. This rounding of the shroud towards the wind-turbines improved the energy performance. The third design which featured a shroud with three smaller wind-turbines with a diameter of 7 m and a 2 m radius fillet around the turbines, improves the energy performance of the design despite the smaller wind-turbines and the decrease in swept area. The fillet enhanced the energy performance, the wind-turbines even produced more energy than the same wind-turbines installed on an open field. However, it should be noted that these configurations were simulated with a wind incidence angle of 0°, which is perpendicular to the shroud and wind-turbines.

3.3 Preliminary product design

The conceptual design of the WE-façade consists of an aerodynamically shaped duct with a certain contraction towards the HAWT wind-turbine in the centre of the duct. The inlets of the duct are dimensionally bounded by the façade openings of the building near the building corner. The duct is situated from the West-façade façade-opening next to the corner column to the South-West façade-opening next to the corner column as shown in figure 3.5.

The inlets of the duct are aerodynamically shaped and curved to realize a certain contraction towards the wind-turbine from the square façade opening inwards towards the location of the wind-turbine. This aerodynamic curved inlet shape and contraction have several functions. The smooth curvature of the inlets and duct allows a better deflected wind-flow towards the wind-turbine in order to partially correct the wind-incidence angle of the incoming wind-flow. This provides a better incoming wind towards the turbine which should improve the energy performance of the turbine. The contraction of the duct towards the wind-turbine provides a more highly accelerated wind-flow through the duct. As explained in paragraph 3.2, it is important to find a balance or an optimum wind-flow through the duct by accelerating the wind-flow and simultaneously prevent the wind-blocking effect. Therefore three variants with different contraction ratios and therefore different sizes of wind-turbines are tested. The variants, test set-up and results are described in chapter 4. The placing of the wind-turbine in reference to the column on the building corner remains the same, centered in the height of the free storey-height. However, the wind-turbine radius is changed and therefore the duct shape and contraction ratio is changed. For first variant the FuturEnergy wind-turbine with a diameter of 1,80 m is assumed, for the second variant the YWS-500 wind-turbine with a diameter of 1,50 m is assumed, the Air X wind-turbine with a diameter of 1,14 m is assumed for the third and final variant. For a complete overview of the turbines please refer to the research report.

Another issue with the design of the WE-façade system could be that the curvature of the duct sides is not symmetrical. This is partly due to the location of the WE-façade in the corner of the building and close to the load bearing column on the building corner and partly due to the size of the installed wind-turbine. This asymmetrical design could lead to stratification of the wind-flow through the duct towards one side with certain wind incidence angles, which is clearly unwanted and could have negative effect on the potential average yearly energy yield. Therefore, three variants are a sequence of smaller difference of curvatures of the duct sides due to the smaller sizes of corresponding wind-turbines. In all three variants, the wind velocity and amplification factors should be measured on two locations near the wind-turbine at approximately 1/3*diameter to determine whether the above mentioned curvature differences have an effect on potential stratification of the wind-flow.

3.4 Type of turbine

For the WE-façade concepts, HAWT turbines are used for all three variants. As investigated before in the research, HAWT and VAWT turbines both have their advantages and disadvantages regarding their energy performance and functionality. Most HAWT turbines turned out to have a generally higher energy performance than most VAWT turbines. Also the available manufacturer data regarding the power output of most rated HAWTs is generally more reliable than for the rated VAWTs. Non-reliable manufacturer data most of the time leads to overestimated power outputs and return of investment (ROI) periods. In addition, most VAWTs have significantly higher investment costs, which automatically increase the return of investment period drastically. Not all HAWTs have a lower ROI period than VAWT turbines. However, the best HAWT turbines of the top 5 lists for both categories of HAWTs contain turbines with significantly lower costs and ROI than the remaining VAWTs. Another advantage of HAWTs over VAWTS is that HAWTs are generally lighter which supports the lightweight requirement of the product.

An important disadvantage of choosing a HAWT is the sensitivity to wind-direction. VAWT turbines are able to receive and use wind-flows from any wind incidence angles. However, with the WE-façade concept as designed, a VAWT turbine would lose its advantage partially due to the confinement of the duct around the turbine as many wind incidence angles are eliminated due to the duct. The building itself eliminates the greater part of usable wind incidence angles, which is needless to say always the case with a building integrated wind-turbine. With the WE-façade as it is, the aerodynamic designed duct would benefit the HAWT in the duct as explained in paragraph 3.2 and 3.3, by its curvature to deviate the flow towards the turbine in order to broaden the range of usable incoming wind-flow incidence angles. Also with a pressure-based system as designed, the wind-flow is created mostly by the pressure differences over the façade and less by the exact wind incidence angles which is also a reason for the choice of a HAWT.

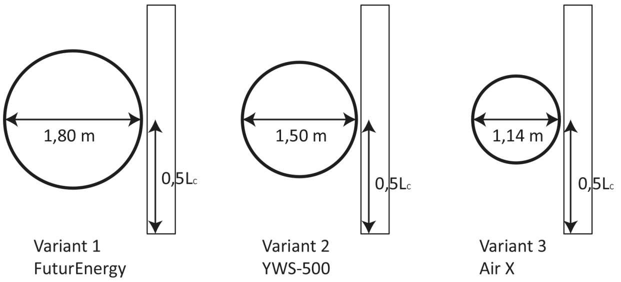


Figure 3.6 | Variant wind-turbines dimensions and placing

Figure 3.7 | FuturEnergy wind-turbine

Figure 3.8 | YWS-500 wind-turbine

Figure 3.9 | Air X wind-turbine

C4

Open field test

This chapter describes the large scale open field test which is conducted in order to test the WE-façade concept as described in the previous chapter. The main aspect is of this test to determine whether the wind-flow through the duct is indeed accelerated compared to the reference wind-speed at the measuring location and document the corresponding amplification factors. Three variants of the concept were tested. These three variants vary in a few dimensional parameters to determine the differences in wind-flow acceleration and patterns in the duct between the variants. Finally, the most suitable variant is chosen and exemplified for further elaboration for the case building "Teun".

4.1 Introduction

In order to test the WE-façade concept, the choice was made to conduct a large scale model test in an open field on a scale of 1:20. Firstly, the purpose of this test is to establish the performance of the product. By performance of the product, the actual potential yearly wind-energy yield is meant. In order to calculate the yearly yield, firstly the performance of the product is measured by time-averaged wind velocities in the duct at the location of the wind-turbine in the duct in relation to the average reference wind velocity on site. These measurements are be conducted for several wind incidence angles in steps of 30° ranging from -30° to 90. These wind incidence angle will further be explained and discussed in paragraph 4.4. In other words, the performance is calculated by the measured wind velocities and corresponding wind amplification factors at the position of the wind-turbine in the duct for multiple wind directions. These measured outputs are then used to calculate the estimated yearly average power output of the WE-façade concept with averaged wind statistics.

Secondly this test provides an opportunity to research the influence of certain design choices regarding the shape of the duct on the wind flow and wind velocity amplifications on a large scale in order to obtain a certain affinity with the product and its potential performance. Aside from the required significant pressure difference over the façades of the building connected by the duct, the performance of the product partly depends on the shape of the inlet ,, curvature with thereby the contraction ratio of the duct and the fitted size of the wind-turbine. Needless to say, a higher amplification factor in the duct is desirable and will significantly improve the average power output of the product as kinetic energy is calculated with wind velocity as a cubic parameter.

4.2 Requirements and considerations

For reduced scale testing, proper scaling and matching of Reynolds numbers is required. However, matching Reynolds number is not possible with such a small scale due to the impossibly high wind velocities needed for similarity. Fortunately, exact matching is not always required if the building has sharp edges as sharp edges of the building ensure fixed separation points of the flow or the minimum required Reynolds number of *Re*=10000 is exceeded. Most edges of the case building “Teun” are sharp. However, the WE-façade product changes the building corner shape which the product will be installed to into a slightly rounded corner. Therefore, the second requirement of a minimum of *Re*=/>10000 is important. A fast calculation of the Reynolds numbers of the scale model as shown below shows that this requirement is met.

$$\mathrm{Re} = \mathrm{VL/v}$$

Re=Reynolds number | V=wind velocity [m/s] | L=building normative length [m] | v= dynamic viscosity of fluid [kg/(ms)]

Full scale | V=5,73 m/s | L=20 m | v=1,983*10-5 kg/(ms)
Re = (5,73*20)/1,983*10-5 = 5779122
Scale model | V=5,73 m/s | L=1 m | v=1,983*10-5 kg/(ms)
Re = (5,73*1)/1,983*10-5 = 288956

Exceeding the Reynolds number minimum is an important reason for choosing a large scale test over a wind-tunnel test. In order to meet the Reynolds number of at least Re=10000 in the wind-tunnel, an impossibly high wind velocity is required especially as not all edges of the building are sharp as explained. Fast concept design choices regarding duct shape for example are also very difficult to model due to the very small scale which is required for the available ABL wind-tunnels. The influence of certain design choices as mentioned above is almost not present on such a small scale.

Choosing a large scale model test instead of CFD testing has several reasons. Firstly, the required system settings most importantly have to represent the correct and accurate wind conditions and wind flow. Obviously for wind-tunnel testing or large scale testing the conditions are also of great importance. However, CFD studies and their used settings need to be validated and verified. Validation of a CFD simulation can be done by matching a similar existing CFD simulation which already has been validated. Another option is validation of the CFD simulation with a wind-tunnel test. Also the advantage of fast testing of conceptual design choices is much faster and more economical with large scale testing than with CFD as most time is spent setting up the CFD test and conditions rather than the actual calculation. Finally, turbulence remains a complex phenomenon which yet has to become a reliable accurate parameter in CFD. Therefore a CFD study does not serve the purpose for this concept testing to test certain design choices in a fast and accurate manner. A large scale test comes closest to reality considering the wind conditions and the mentioned scaling issues.

4.3 Test cases

Three WE-façade product concepts are tested which vary in a few interrelated parameters. Variant 1, 2 and 3 all vary in the size of the wind-turbine. However, not only does the wind-turbine vary in size, by reducing its size the contraction of the duct is increased in relation to the inlet size in order to fit properly around the turbine. The purpose of this variation in contraction ratio is to find a balance in the so called Venturi-effect of accelerated wind-flow and the wind-blocking effect as explained in chapter 3. While a larger contraction could provide higher amplifications in the duct and therefore potentially a larger energy output of the wind-turbine, a relatively steep contraction could cause wind-blocking in the duct, causing wind to flow around it instead of through it.

In table 4.1 the variants and their corresponding contraction ratios are shown. The contraction ratio is dimensionless and is calculated by dividing *i* the inlet height by *c* the contraction height at the position of the wind-turbine, in this case the height of the wind-turbine, as shown in figure 4.2.

In addition, a larger contraction due to a smaller wind-turbine also causes different curvatures of the duct. The position of the wind-turbine next to the column on the building corner centered between two storey-floors remains unchanged which automatically causes a steeper curvature of the duct towards the smaller wind-turbine. Due to this altered shape of the duct, variant 1 shows the strongest asymmetry of the duct side curvatures. Variant 1 shows an almost flat side and a curved side while the variant with the smallest wind-turbine variant 3 shows the most steeply curved duct towards all sides of the inlet. These differences in curvatures of all variants provides an opportunity to test whether the asymmetry of the duct influences the amplification in the duct or whether the wind-flow follows a straight path and is not slightly separated or accumulated to a certain side in the duct. Separation or accumulation of the wind-flow to a certain side of the duct would cause different wind velocities in the separated parts of the duct which could have a negative effect on the potential performance and therefore wind-energy yield of the turbine.

4.4 Test set-up & method

The beach at Brouwersdam in Zeeland, The Netherlands, is chosen to conduct the large scale testing for its strong average wind velocity and small roughness length z_0.

As shown in figures 4.4 and 4.5, Wieringa and van Rijkoort (1983) measured less deviation in wind direction for higher wind velocities in a time interval of 10 minutes. The smallest values were measured for wind above open water, as well as mechanical turbulence being dominant over thermal turbulent effects at higher wind velocities.

The scale model of the building (1:20) is modelled from the ninth floor up to the rooftop, to represent the building height from the displacement height of the wind profile in the vicinity of Teun, combined with limitations by logistics.

Time-averaged wind velocities are measured inside the system scale model at two locations with exception of variant 3 in which velocities are measured on 1 location, as shown in figure 4.6.

Terreintype	z_o(m)	σ_u/U	σ_d	
			$U = 4$ m/s	$U = 8$ m/s
Open water	0,0002	0,08	3°	2
Open terrein	0,03-0,1	0,16	4°	3°
Ruw terrein	0,1-0,3	0,22	8°	6°
Zeer ruw terrein	0,3-0,7	0,35	15°	12°

Figure 4.5 | Angular deviation (σd) for different terrain roughness (z_0) (Wieringa and van Rijkoort, 1983)

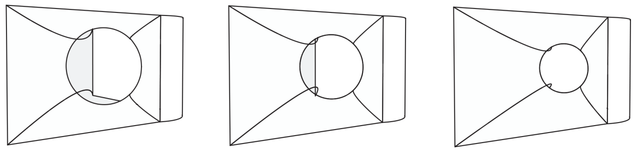


Figure 4.1 | Schematic impression of differences of the three test cases | Left variant 1, middle variant 2 and right variant 3

	Variant 1	Variant 2	Variant 3
Turbine	FuturEnergy	YWS-500	Air X
c	1,8	1,5	1,14
i	2,2	2,2	2,2
i/c	1,22	1,47	1,93

Table 4.1 | Variant contraction ratios i/c

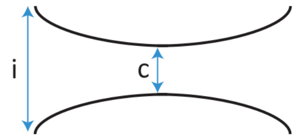


Figure 4.2 | Contraction ratio parameters of a duct section

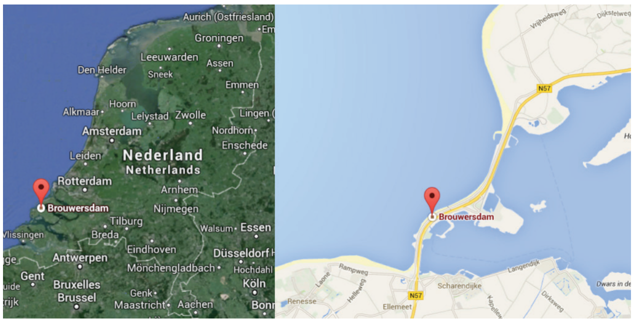


Figure 4.3 | Test location at Brouwersdam, Zeeland, The Netherlands (Google Maps, 2014)

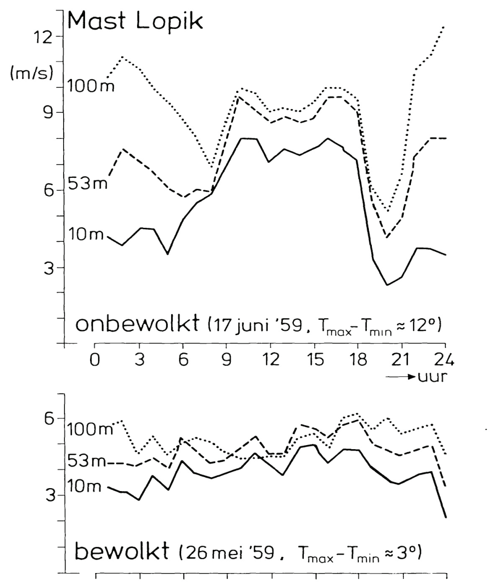


Figure 4.4 | Daily velocity fluctuations (Wieringa and van Rijkoort, 1983)

Measurements on these two locations are conducted in order to obtain data on wind velocity stratification in the duct which may have a large influence on a turbines performance as explained before. The two measured time-averaged wind velocities U_{duct} [m/s] inside the duct have to be related to a reference free-stream wind velocity U_{ref} [m/s] at model height H to obtain dimensionless amplification factors γ [-] inside the duct, given by:

$$Re = \frac{U_{duct} * r}{v} \tag{4.1}$$

The amplification values are obtained in order to determine the performance of the variants and compare the three variants in an objective manner as wind velocity and wind incidence angles are fluctuating parameters. Wind velocity on its own is certainly not enough to determine the performance of the product without a reference wind speed. The reference wind speed U_{ref} is determined with a sonic anemometer by averaging wind velocities over a period of time T_{avg}. The latter is given by the time it takes for the average free-stream wind velocity at location 2 (without the model) to equal the average wind velocity at location 1 and should be at least 10 minutes, which is a standard measuring period for wind statistics. Tavg is obtained on-site with two thermal anemometers. The reference wind angle of incidence αref is averaged by averaging wind direction from the two-dimensional sonic

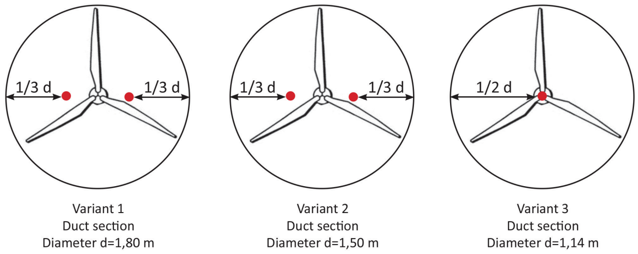


Figure 4.6 | Measuring locations in the ducts

anemometer at location 1. By turning the model towards different directions, data on different angles of incidence can be gathered, in this case from -30° to 90°. It can be expected that γ drops to near zero beyond 90°, while being the highest from 0° to 30°. Since the product-models are symmetrical, data on these angles can be mirrored at -45° to provide results for angles of incidence from -45° to -180°.

Wind-turbines provide a certain blockage on the flow through the duct. However, the turbine volume is not represented in the scale models. While obstruction from turbines can have a significant effect on the air-flux through a duct, as proved for the Pearl River Tower in Guangzhou by Li et al. (2013), it should be recognized that the actual wind-turbine performances could slightly drop due to its own blockage. It should be noted that the turbines in the case of the Pearl River Tower are drag driven type turbines.

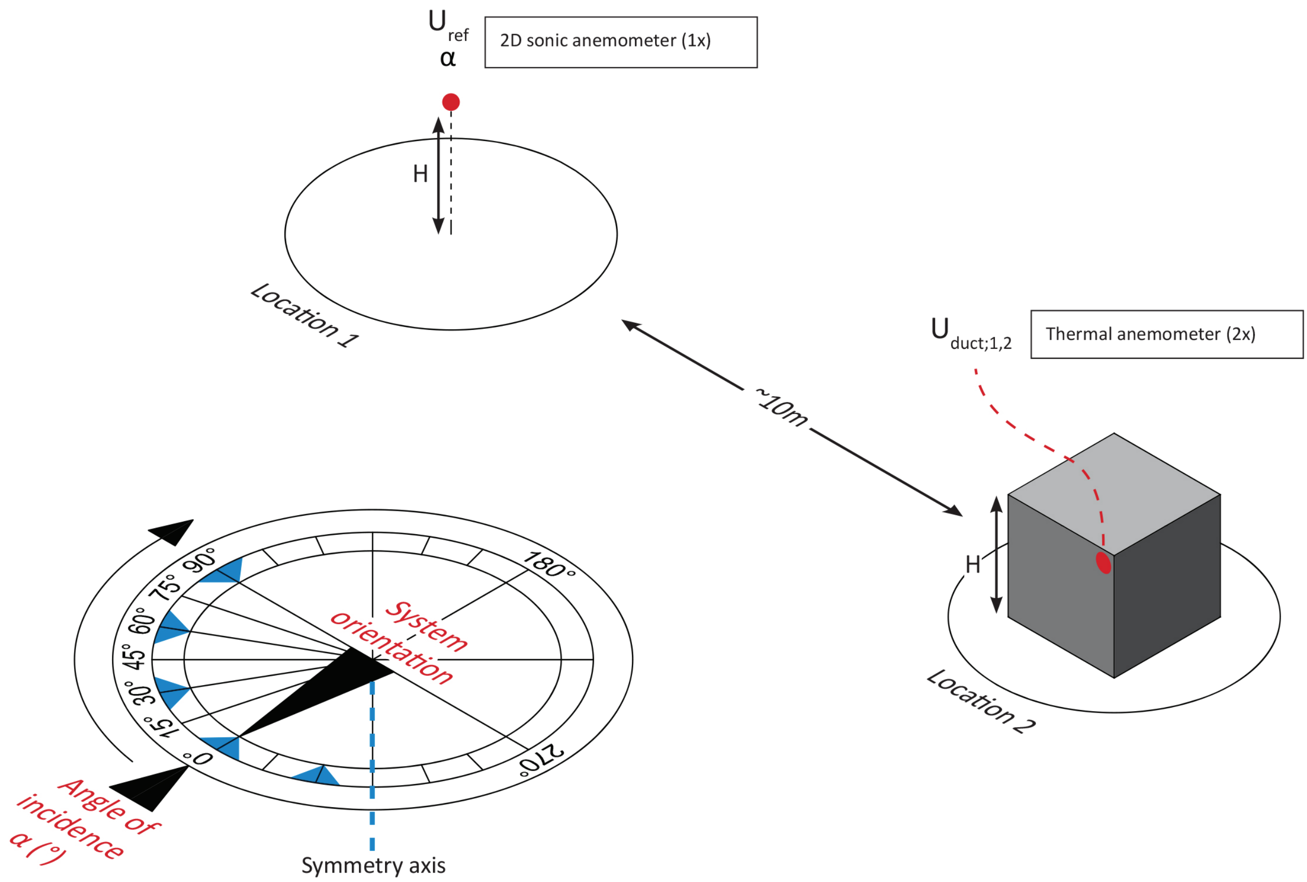


Figure 4.7 | Test set-up

4.5 Results

As explained in the previous paragraph, the results of the three WE-façade variants are firstly compared in the first paragraph by the amplification values in the duct. In other words, purely the measurement values are compared. Further on in this paragraph the measurement results are combined with yearly averaged wind statistics and wind-turbine potential performance in order to provide an estimate of the potential yearly power output of each variant. The measurement results are time average over 1 minute intervals for Tavg. Figure 4.8 shows the actual measuring locations in the duct at the location of the wind-turbine, as the measuring locations as shown in the previous chapter slightly differ from the actual measuring locations. Paragraph 4.6 presents the drawn conclusions over the measurement results and in chapter 4.7 a general discussion and further recommendations are described.

4.5.1 | Measurement results

As in variant 3 only 1 measuring location for the wind velocity was possible, variant 1 and 2 are firstly compared. Comparing variant 1 shown in graph 4.1 with variant 2 shown in graph 4.2, the measurements trend lines seem to correspond. Both variants show an irregular course over the first range of wind incidence angles. The amplification factors stay mostly around and above ɣ=1 from 0° to 30° after which the values decline towards low values around 60° to 70° and then increase again slightly towards 90°-100°.

As expected, variant 1 shows a significant difference of amplification values between the two measuring locations in the duct. The curvier side of the duct at ɣ-708 shows higher amplification factors than the less curved side at ɣ-837, which could be due to flow separation or stratification in the duct caused by difference in flow deflection and guidance towards the measurement locations in the duct. This difference is probably caused by the difference in curvature and the curvature guidance with certain strongly oblique wind incidence angles which could be an explanation for when comparing the measurements of variant 1 to variant 2, the less asymmetric duct of variant 2 shows less differences in measurement values between the two measurement locations in the duct.

Comparing the measurements of variant 3 as shown in graph 4.3 with variants 1 and 2, the general trend of increasing amplification values towards wind incidence angle 0° and decreasing values from 30° towards 40° corresponds. However, variant 3 shows a less irregular course over the first angles of incidence from approximately -30° to 0°. Variant 3 also shows a larger range of amplification values above ɣ=1 ranging from approximately -10° to 35° and shows generally slightly higher amplification values across the general trend line than variants 1 and 2.

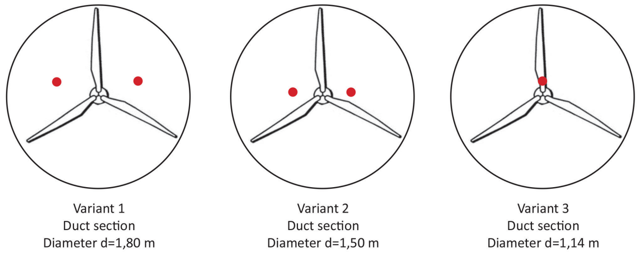


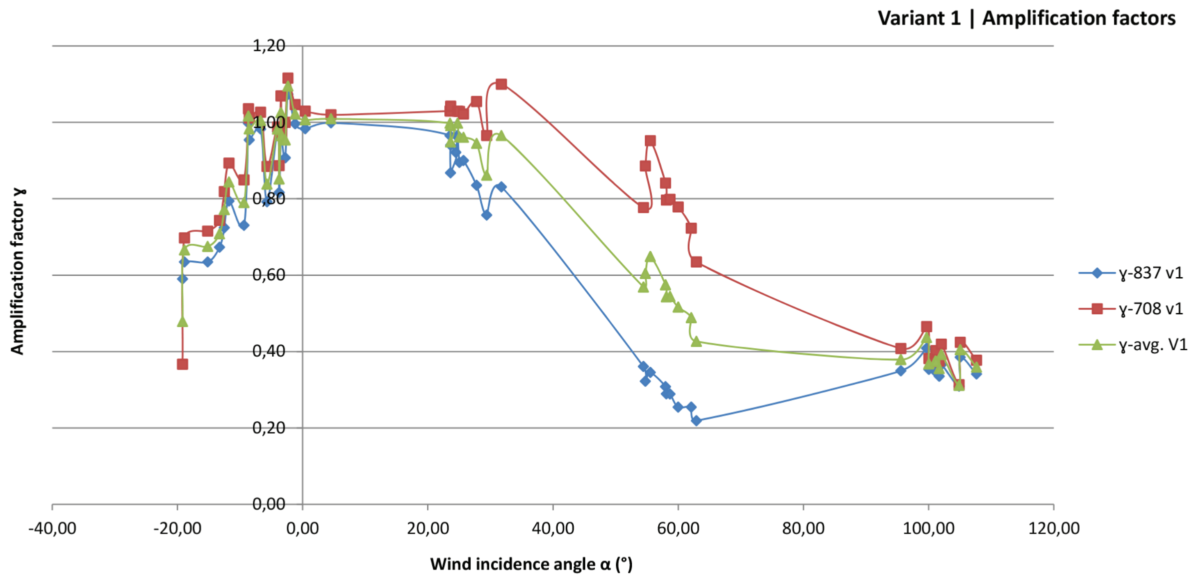
Figure 4.8 | Actual measuring locations in the ducts

All three WE-façade concepts are based on pressure differences over the connected building façades, which means that the wind-flow is mostly driven by the pressure differences on both facades and less by the wind incidence angle of the incoming wind-flow than with wind-turbines placed outside. Of course the wind incidence angles do have a certain effect on the pressure differences over the façades; however, this effect is less significant. Therefore, the stronger contraction or the larger decrease of the cross-section of the duct of variant 3 probably provides higher acceleration of wind velocity. The stronger curvature probably provides more straightened wind-flows towards the measurement location at the wind-turbine location which provides generally higher values. These phenomena are further explained and discussed in paragraph 4.6.

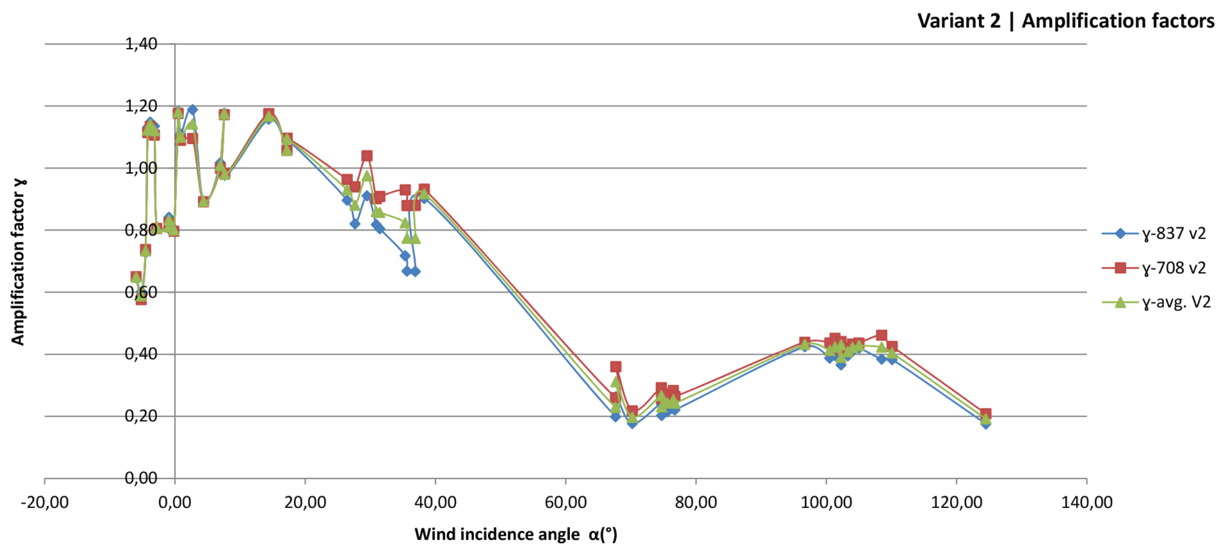
As the general trend of amplification values across the spectrum of wind incidence angles seems quite similar for all variants, variant 3 shows generally slightly higher values. This could be an advantage for variant 3, however variant 3 also includes the smallest wind-turbine of the three. Higher amplification values and values above the ɣ=1 boundary are not necessarily the only conditions for choosing a concept for further elaboration. The performance of the concept when including the wind statistics are more important and shows whether its performance without statistics matches the wind statistics to generate a high average power output. This is investigated in by Boon and Eskander (2014). In addition, the wind-turbine potential wind-energy output is also of great importance which is dependent on several factors such as the cut-in and cut-out wind velocity and its size of swept area. In the next paragraph the measured outputs are combined with yearly averaged wind statistics of Breda, in order to calculate and compare the potential yearly average outputs of all variants.

4.5.2 | Expected versus measured yearly wind-energy yield

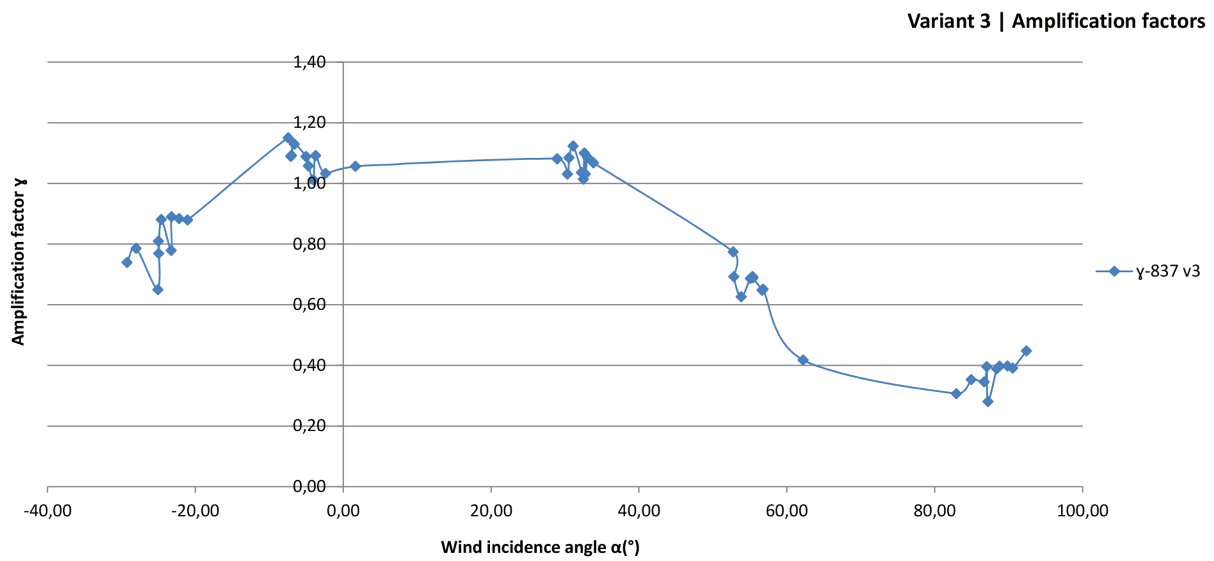
In this paragraph all measurement results from the previous paragraph are used to calculate the average yearly yield in kWh with wind statistics of the small city of Breda where the case building “Teun” is located and the corresponding return of investment period (ROI). In this case, the ROI is calculated with the turbine costs and costs benefits by its yield leaving out the inevitable costs for manufacturing and instalment of the building element itself in order to solely



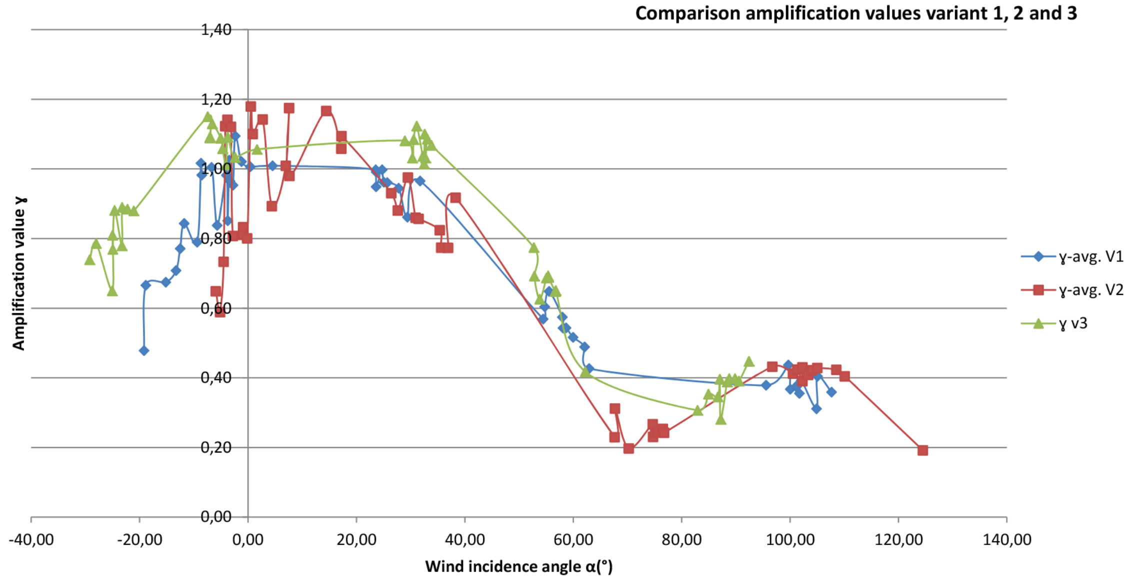
Graph 4.1 | Amplification values of variant 1 with T=1



Graph 4.2 | Amplification values of variant 2 with T=1



Graph 4.3 | Amplification values of variant 3 with T=1



Graph 4.4 | Comparison of amplification values of variants 1, 2 and 3

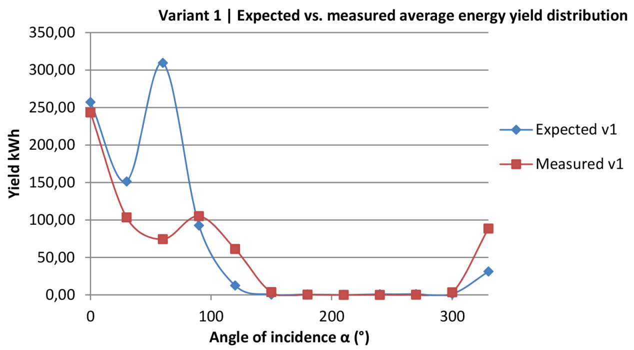
compare the performance of the duct and turbine. These parameters are then compared to the potential yearly average yield in kWh and the potential ROI as established in the research by Boon and Eskander (2014) for each wind-turbine. In order to determine whether a variant of the WE-façade concept performs well, its calculated yearly yield and thereby the ROI should be at least equal or higher than its potential yield and ROI. For integration of the measurement results with wind statistics, the orientation of Teun is used to generate the average yearly energy yields. In this case this orientation is with 270°. The most optimal orientation for the WE-façade and Teun would be around 300° which is slightly more towards the West. The comparison of the potential performance to the measured average performance is shown in table 4.2.

Solely comparing the calculated average yearly yield in kWh to the expected potential performance, as can also be concluded from the previous paragraph, variant 3 seems to perform best by a higher power output of +24,25% than its expected potential yearly yield. Therefore, also the ROI period is also decreased compared to the expected ROI. Variant 2 also performs slightly better than its expected performance with +6,77%. However, the difference is not significant as with variant 3. The first variant performs worst with a decrease of the average yearly yield by -25,44%. Taking only the calculated average yearly yield based on measurements into account, variant 1 produces the highest power output with the lowest ROI due to the larger and better performing FuturEnergy wind-turbine. The second best is variant 3 in this case with a slightly higher ROI, however with a significantly lower total power output of 40% less with the Air X turbine compared to variant 1. The better performance of variant 3 is probably due to the higher contraction ratio and thereby a better aerodynamically curved duct as mentioned before and is further explained in the next paragraph.

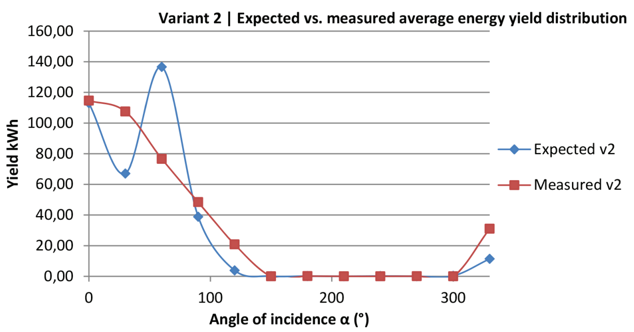
Graph 4.5, 4.6 and 4.7 show the measured and measured versus the expected average energy yield distribution of the used turbine for the corresponding variant per interval of 30° angles of incidences as calculated in the research of phase one versus the measured energy yield during the test. Comparing the three variants measurement results on the intervals of 30°, the measurements of all three variants show similar trend lines with less high peaks and a smoother course than the expected trend line. The expected energy yield shows a small peak around 0° and a larger peak around 60° while the measured energy yield shows a generally decreasing trend from the peak around 0° on to 150°. This can be explained by the fact that the expected trend lines have been generated based on data of mean pressure differences over closed building façades. Needless to say, the measured data were measured in the duct as explained before, not on closed parts of the façade. The duct opening probably causes pressure alleviation over the connected building façades as the built up pressure against the façade decreases due to the open parts. However, the smoother trend line of the measured data is probably more beneficial for the total average energy yield as the more extended peak range provides less sensitivity to wind incidence angles than the higher peak of the expected trend line. In other words the expected trend line shows higher dependency on a smaller range of wind incidence angles for a high average yearly energy yield after which the expected yield drops significantly fast towards 0 energy yield for the other wind angles of incidence.

Variant	Wind-turbine	Blade diameter in m	Expected yearly yield kWh	Expected ROI in years	Measured calculated yearly yield kWh	Measured calculated ROI in years	Yield difference in percentage
1	FuturEnergy	1,80	858	6	684	7	-25,44
2	YWS-500	1,50	372	12	399	11	6,77
3	Air X	1,14	203	10	268	8	24,25

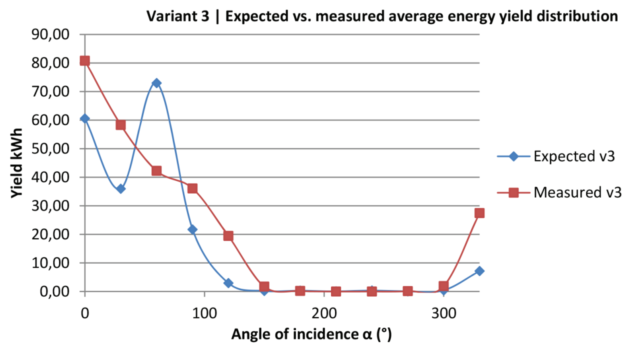
Table 4.2 | Comparison potential performance of variants to measured average performance



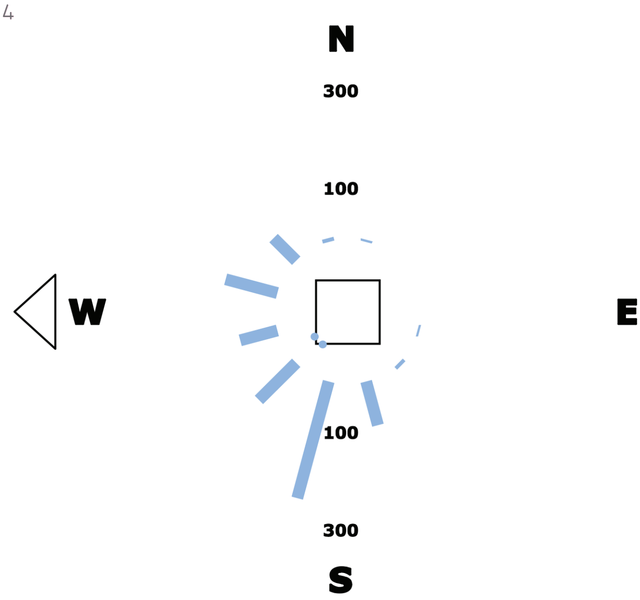
Graph 4.5.1 | Variant 1 expected versus measured average yearly energy yield distribution



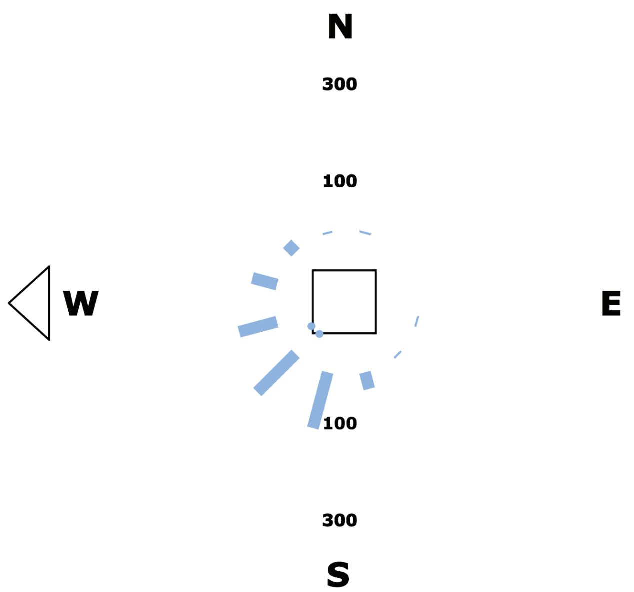
Graph 4.6.1 | Variant 2 expected versus measured average yearly energy yield distribution



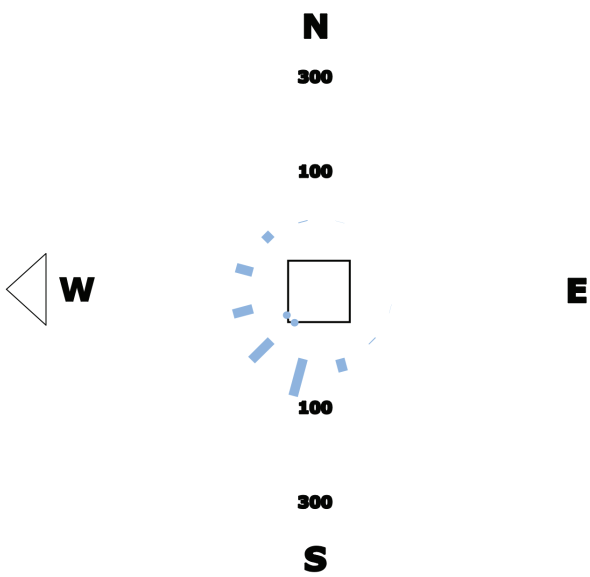
Graph 4.7.1 | Variant 3 expected versus measured average yearly energy yield distribution



Graph 4.5.2 | Variant 1 measured calculated average yearly energy yield distribution



Graph 4.6.2 | Variant 2 measured calculated yearly average energy yield distribution



Graph 4.7.1 | Variant 3 measured calculated average yearly yield distribution

4.5.3 | Comparison tested duct performances with potential performances of other turbines

In this paragraph the performance in terms of measured amplification values of the third and best performing variant with the corresponding contraction ratio is merged and compared with the other two selected wind-turbines namely the FuturEnergy and the YWS-500 in table 4.3. Comparison of the duct performance with a different wind-turbine should be done with similar dimensional ratios in order to maintain the contraction ratio and the corresponding amplification values for all wind incidence angles. By maintaining the contraction ratio, the assumption is made that scaling the duct while maintaining the contraction ratio should barely have an effect on the aerodynamic performance in terms of wind velocity acceleration. As mentioned before, Blocken et. al. (2011) investigated the contraction ratio i/c as a dimensionless number to investigate the influence of variation of the contraction height in relation to the inlet height of the Ventec roof. This is done for the reason that Blocken et al. assume that an ideal contraction ratio of a system exists and creates a balance between the so-called Venturi-effect and the wind-blocking effect which is not bound to dimensions as the contraction ratio is a dimensionless number. In other words, scaling the duct while maintaining the same contraction ratio, should provide similar measurement results of amplification values. Therefore, increasing the size of the wind-turbine increases the duct height at the location of the wind-turbine which also increases the inlet height in order to maintain the contraction ratio.

Merging the duct performance and the corresponding amplification values of the second and third variant with the best performing wind-turbine FuturEnergy in terms of average yearly yield, the yield significantly increases in comparison to the same variant with the chosen variant turbine Air X. Also in comparison with the expected yearly yield, the power output significantly increases. The performance values of variant 3 combined with the YWS-500 also show an increase of yearly average yield in comparison to the expected average yield and the original chosen turbines' power output. In addition, needless to say the ROI period of all of these trial variants as presented in table 4.4 decreases as a result of higher power outputs.

As variant 3 in combination with the FuturEnergy turbine performs best, this combination cannot be implemented to the case building "Teun" due to the large inlet-height needed to maintain the required contraction ratio. This is also the case for variant 3 in combination with the YWS-500 turbine. As indicated in chapter 2, the total storey-height is 3 m, the free available storey-height for implementation of a WE-façade system is 2,61 m. This leaves only variant 2 in combination with the FuturEnergy as the only possible option for "Teun", which is the second best variant with an average yearly yield of 927 kWh and a ROI-period of 5 years. In comparison with the original variant 2 with the YWS-500 turbine, this combination has a 43% higher power output and 7,4% higher power output than the expected yield. It should be noted that the ROI calculation as presented only includes the total costs of the wind-turbine in comparison to its average yearly energy yield and excludes the costs for manufacturing and instalment of the duct.

Figures 4.9 and 4.10 show photographs of two of the variants installed in the test building on the test location.

	Variant 1 (tested)	Variant 2 (tested)	Variant 3 (tested)	Variant 2 (not tested)	Variant 3 (not tested)	Variant 3 (not tested)
Turbine	FuturEnergy	YWS-500	Air X	FuturEnergy	FuturEnergy	YWS-500
c	1,80	1,50	1,14	1,80	1,80	1,50
i	2,20	2,20	2,20	2,65	3,47	2,90
i/c	1,22	1,47	1,93	1,47	1,93	1,93

Table 4.3 | Calculation of contraction ratios

Variant	Wind-turbine	Blade diameter in m	Expected yearly yield kWh	Expected ROI in years	Measured calculated yearly yield kWh	Measured calculated ROI in years	Yield difference in percentage	Yield difference with current variant turbine
2	FuturEnergy	1,80	858	6	927	5	7,44	43,04
3	FuturEnergy	1,80	858	12	1139	4	24,67	76,47
3	YWS-500	1,50	372	10	492	9	24,39	54,47

Table 4.4 | Comparison of variant performances with performances of other wind-turbines Table 4.4 | Comparison of variant performances with performances of other wind-turbines

Figure 4.9 | Photograph of the test, the building with variant 1

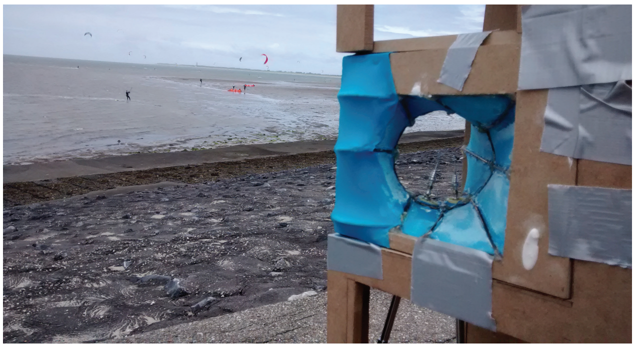


Figure 4.10 | Photograph of the test, the building of withvariant 2

4.6 Conclusions

Of the tested three variants, the third variant performs best when only considering the amplification values in the duct. This variant provides the highest acceleration values and therefore produces the highest percentage of average yearly yield over the expected potential average yearly yield for the type of installed turbine. This is probably a result of the more optimized contraction ratio compared to the other two variants, in order to accelerate the incoming wind-flow while maintaining a certain balance in order to avoid wind-blocking.

The first variant has the highest power output which is due to the larger turbine with the highest potential yearly yield, however this variant scores worst as it does not meet the expected potential yearly energy yield. The larger asymmetry in the duct is probably the cause for separation of wind-flow in the duct as can be concluded from the results of the first variant. The less curved side causes less acceleration or even deceleration of the wind-flow in comparison to the more curved side of the duct which is the side of the column. It is therefore desired to have a symmetric duct or as symmetric as possible to avoid flow separation and evenly distributed wind-flow and amplification factors in the duct.

Stronger curved ducts due to a higher contraction ratio i/c, which is the inlet height in relation to the contraction height, provide higher amplification values throughout most wind incidence angles as can be concluded from comparison of the results of the three tested variants. According to Blocken et al. (2011), the optimal contraction height does exist. However, the investigated variants in this test do not present the most optimized variant or contraction ratio yet. The most optimized contraction ratio would provide the optimal balance between the so called Venturi-effect and the wind-blocking effect. It should be noted, as mentioned before, in this case the Venturi-effect is used as a term for acceleration of non-confined wind-flows while in essence the Venturi-effect should only be used for confined flows.

Scaling the duct of the second or third variant and while maintaining the contraction ratio i/c in order to fit a larger and better performing wind-turbine will probably maintain its acceleration performance while increasing the average yearly yield. However, this means that in order to retain the contraction ratio with a larger contraction height, the inlet height also increases. In case of case building “Teun” the best possible fit would be variant 2 in combination with the FuturEnergy turbine. Therefore variant 2 with the FuturEnergy is chosen for further elaboration. The elaboration of this variant in terms of building technology and building physics, namely materials, connections and joints to the building, fabrication process and construction order are discussed in the next chapter.

For all variants, the distribution of the measured average yearly energy yield shows a smoother more evenly distributed trend line than the expected distribution of average yearly yield. The expected distribution shows a higher peak over a smaller range of wind incidence angles. This difference is caused by a certain pressure alleviation which occurs due to the opening of the duct as the data for the expected distribution of average yearly yield was collected for closed building façades instead in the openings of the duct. However, the more evenly distributed course is more beneficial towards the product as it shows a decrease of its sensitivity for certain wind incidence angles.

4.7 Discussion and recommendations

As this research provides the best researched option of the WE-facade variants for the case building "Teun", certainly more research is needed as this test is limited to only three options. Three variants with their different corresponding contraction ratios i/c were investigated. However, the most optimal contraction height has not been established yet. In order to determine the optimal contraction height, more contraction ratios should be tested, in particular larger contraction ratios as the largest ratio tested, is at this point the most optimal due to the lack of larger ratios. In essence, the optimal contraction ratio provides the optimal balance between the Venturi-effect and the wind-blocking effect as stated by Blocken et al. (2011), which should provide the highest amplification values in the duct and therefore a significant increased average yearly energy yield. Although an optimal contraction height should exist, it is uncertain whether scaling the inlet and contraction height while maintaining the contraction ratio as suggested in paragraph 4.5 has an effect on the performance of the duct. Therefore, it is essential to investigate the effects of scaling the product dimensions in order to ascertain the independency of the dimensionless contraction ratio.

The variant performances in terms of amplification ratios are not bound to the wind-turbine performances while the final choice for the variant is. Variant 2 was chosen for further elaboration due to the larger and better performing wind-turbine suitable with variant 2 for implementation in "Teun" while maintaining the contraction ratio, as actually variant 3 performed better. However, the average energy yield performances are linked to the current available turbines and their performances. As wind-turbines are constantly in development, it is not unlikely that in the future better performing wind-turbines become available in the same size or smaller than the currently used ones for the generated results which could provide the possibility of using variant 3 with a better performing turbine.

This research is also limited to the case building "Teun", a building with a limited height and type of façade. Performing the same research on other types of buildings will probably provide different measurements. Firstly, it could be that the openings of the loggias around the WE-façade element cause a different wind-flow and different pressure distributions over the façades of the building and/or even (local) pressure alleviation which influences the wind-flow through the duct. Therefore, it is recommended to carry out tests to investigate the influence of the open façade parts of the loggias. Secondly, "Teun" is a square building, it is expected that with a rectangular building the measurements would be different. As investigated in the research in phase one, rectangular buildings of the same height cause higher acceleration around the building corners. On the contrary, pressure differences around the corners of rectangular buildings on the wind-ward and side façades are expected to decrease in comparison to square buildings of the same height which could negatively affect the performance of the system. Therefore, it is recommended to test potential case buildings individually for accurate performance indication of the WE-façade. Thirdly, the variants were tested with only one type of shape of the column on the building corner which is an oval shape. It is certain that changing the corner shape of a building has an effect on the pressure distribution and pressure differences on the façades as also established in phase one of this report. However, the effect of corner shapes on the performance of the duct has not been investigated. It is expected that a curvier round shape could provide slightly higher pressure differences over both sides which is beneficial for the wind-flow through the duct. Such a rounder shape could also provide slightly better amplification values for wind incidence angles from 0° towards the symmetry line of the WE-façade around -45° due to the expected better guidance of the wind-flow by the curve towards the turbine. A sharp corner could also provide a better overall performance due to the expected higher pressure difference over the façades, however, it is also expected that for strongly oblique flows from angle of incidence of 0° to the symmetry line of -45°, the amplification values in the duct could decrease due to the deflection of the wind-flow by the sharp corner shape.

This test was performed for the case building "Teun" without the surrounding buildings. In order to attain a complete understanding and complete data on the performance of a WE-façade system, research should also be conducted with the surrounding buildings as these certainly have an effect on the wind conditions and flow around the building as well as the turbulence intensity.

Lastly, imperfections and inaccuracy of the tested scale models could cause different measurements than measurements which would be obtained from a more scientific test model and conditions. Surfaces were not as smooth and perfectly aerodynamically shaped as designed, in order to ensure the best measuring conditions. In addition, it has not been determined whether the testing conditions were best suited for carrying out such a test. However, this test was conducted in order to establish a non-scientific feeling and performance indicators for such a product and generates new opportunities and topics for further research in this field.

C5

Product design proposal

As concluded from the previous chapter, the best option and fit of the WE-façade variants as presented is the second variant in combination with the FuturEnergy wind-turbine. In this chapter further elaboration of this variant is presented as the goal is to present a proposal for the WE-façade building element. Firstly, a proposal of the final design is presented conceptually. In the second paragraph, further elaboration is presented and described namely the choice of materials and their composition combined with building physics and technical/structural design related topics and considerations. The third paragraph gives an estimation of the maximal total costs in relation to the return of investment period. Paragraph four consists of a description of the fabrication process. The fifth and final paragraph describes the sequence of construction phases of the WE-façade product and presents the technical details of the product design and connections.

5.1 Product shape and design

In this chapter a conceptual design proposal of the WE-façade duct for the case building "Teun" is presented. Figure 5.1 shows one WE-facade product installed in the case building "Teun". Then, the shape of the duct is presented conceptually in several views in figure 5.2 to 5.4 in order to form an impression of the complex shapes of which the product consists which will further be elaborated on several topics in the next paragraphs. These double curved shapes the duct are the leading factor for the elaboration in terms of material and material characteristics as most traditional building materials are unsuitable for the fabrication of these types of complex shapes. In order to keep the costs to a minimum and the construction process relatively simple, the duct consists of 4 elements, the 5th element is the rounded shape around the outside of the column. These five elements are fixated to the inlets at the façade openings similar to window frame elements. These design choices are further elaborated in the next paragraphs.

Figure 5.1 | Impression of "Teun" with an installed WE-façade product

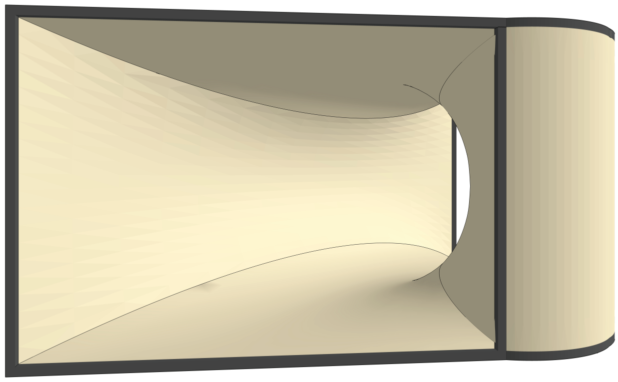


Figure 5.2 | Impression of the WE-façade product and duct shape | Front view

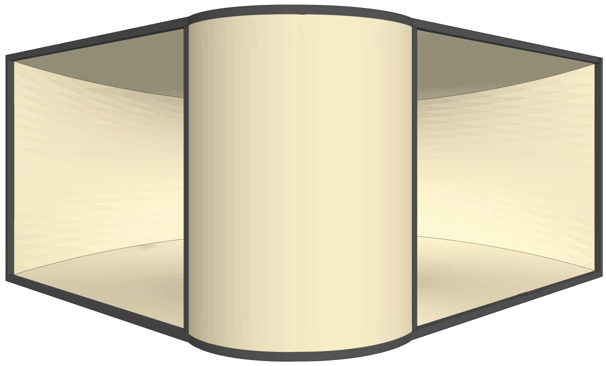


Figure 5.3 | Impression of the WE-façade product and duct shape | Oblique front view

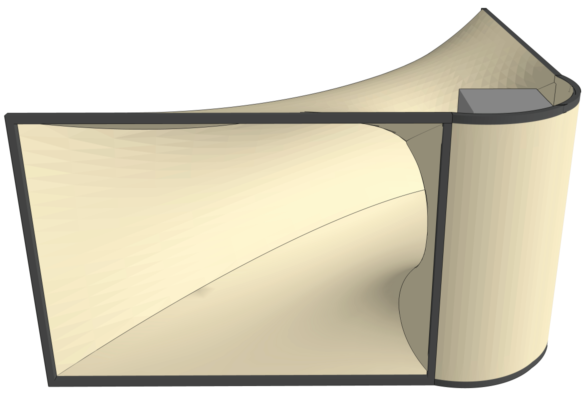


Figure 5.4 | Impression of the WE-façade product and duct shape | Perspective view

5.2 Materials

In chapter 2, the product requirements are described for the WE-façade product. Considering the most suitable materials for the elaboration of the building element, important requirements impose a certain direction for the choice of materials in order to meet these requirements. The WE-façade product should first of all be a system independent add-on which could be installed on to any suitable building easily without major changes to neither the product nor the building structure. Therefore, the product should be lightweight in order to fit to most buildings and should not require additional measurements regarding structural reinforcements to the building or product. A system independent add-on product also implies a self-supporting element. In addition to these requirements, the aerodynamic shape of the duct imposes certain material restrictions. The double curved shapes of the duct cannot be manufactured with just any traditional building material. Considering these requirements, after investigation of materials properties such as mechanical properties, weight and fabrication process, glass fibre reinforced polymers referred to as FRP is chosen as the main material for the duct of WE-façade.

5.2.1 | *FRP versus traditional building materials*

FRP's are composite materials which consist of a polymer resin reinforced with glass fibres. FRP as a building material has certain advantages and disadvantages in comparison with traditional building materials such as steel, aluminium or concrete for the use for the WE-façade product. In this paragraph, the general characteristics of FRP are discussed and compared to traditional building materials and techniques. The choice for FRP is discussed based on each material characteristic, advantageous or disadvantageous. General material characteristics of FRP are:

- Lightweight material
- Good mechanical properties
- The shaping and colour possibilities are endless
- Durable in the sense of lifetime
- Quite good thermal insulation with sandwich layering of k= 0,3-0,4 W/mK (In combination with insulating core materials the thermal insulation could be quite high (for example with PUR = 0,035 W/mK)
- Material behaviour in case of fire requires attention and adequate measures
- The thermal expansion coefficient requires adequate measures for joints and connections

(Stichting bouwresearch, 1985)

5.2.2 | *Lightweight*

An important characteristic of FRP is that it is a lightweight material which is a great advantage compared to traditional building materials, especially when considering its mechanical strength properties. This characteristic also provides an advantage for the WE-façade considering the instalment possibilities to new and existing buildings. New buildings are built taking into account stricter building regulations nowadays, considering the construction properties compared to older existing buildings. Therefore, with a lighter product probably more buildings would be suitable for implementation of the product without changes or additional reinforcement of the building construction. In table 5.1 the main material properties of FRP compared to other traditional building materials are displayed.

5.2.3 | *Mechanical properties*

For the WE-facade especially the combination of the low mass weight and the bending strength are important characteristics for choosing FRP. With FRP as a building material, the bending strength is normative due to the low E-modulus. The duct is mounted on both sides to the frame of the façade opening and has a large free span length of a maximum of 5,5m. This free span therefore requires a certain strength and stiffness in order to provide the necessary mechanical properties needed for such an element to be self-supporting and require fewer parts by less or no division of the duct length. These properties will need investigation for each building in which WE-façade could be implemented to in order to determine the exact mechanical properties and requirements. In table 5.1 mechanical material properties are displayed comparing FRP with other traditional materials.

Material	Mass weight kg/m³	Tensile strength N/mm²	Compression strength N/mm²	Bending/ flexural strength E-module (bend) N/mm²
Steel	7800	235	235	210000
Aluminium	2700-2800*	70-700*	470	70000
Concrete (reinforced)	2400-2500*	20-30*	20-30*	10000-19000*
GRP (bidirectional weave)	1550-1800*	220-280*	160-240*	12000-20000*
GRP (unidirectional weave)	2000	650-730*	350-400*	30000-33000*
Hardwood/Tri- and multiplex	800-700*	10	10	7000-12000*

**dependent on material composition*

Table 5.1 | Mechanical material properties of a selection of building materials (Stichting Bouwresearch, 1985 and Spierings et. al., 2004)

5.2.4 | Shape

Another advantage of FRP is that it is a material which can be relatively easily moulded into many shapes which is a required characteristic for the aerodynamic shape of the duct, with the most common techniques for processing FRP. Concrete for example could also be moulded into any shape. However, FRP remains the best option for the WE-façade due to its light weight and higher shape accuracy regarding material dimensional tolerances and the possibility of more slender parts compared to concrete. Metals such as steel or aluminium are also mouldable into single curved surfaces with traditional moulding techniques. However, when it comes to double curved surfaces, these moulding techniques are unsuitable. Nowadays new techniques for moulding metals and glass in any shape are in development. For example, Karel Vollers introduced a prototype of a computer-controlled adjustable mould for bending building materials such as metals and glass into any desired shape, single or double curved as shown in figure 5.5. As the idea seems revolutionary and the adjustable mould would be perfectly suited for fabricating the duct shapes of the WE-façade, Karel Vollers' adjustable mould is still in development.

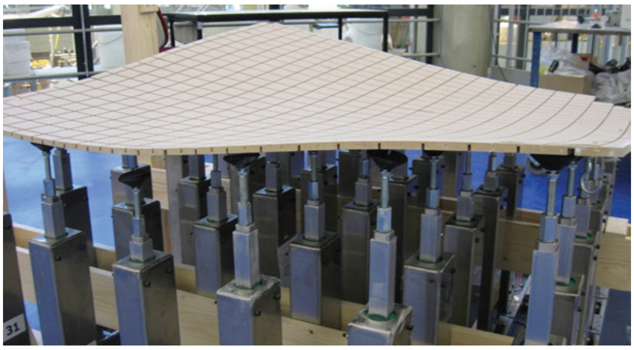


Figure 5.5 | Karel Vollers adjustable mould prototype (Schipper, 2013)

Another example of a technique for moulding metals into double curved shapes is explosive moulding. With this technique metals are moulded into the desired shape with controlled explosives under water. Explosive moulding does have several disadvantages as this technique is highly expensive compared to other moulding techniques and is characterized by a significantly long-term and labour-intensive production process (De metaalgids, 2014). In addition, this moulding technique is only suitable for metals.

5.2.5 | Durability, material properties and composition

Durability when considering lifetime could be quite high with the right composition of resin and glass fibres and optional additional substances. Stichting bouwresearch (1985) classified the types of resin into 6 categories ranging from general purpose resin to resin with special requirements such as impact resistance. The order from first to the last category indicates increasing material quality in terms of durability and chemical resistance. In case of the WE-façade mechanical properties are important and also fire resistance is a very important decisive characteristic of the composition of the material in order to satisfy the fire safety regulations. Category 5 is most suitable resin which is described by Stichting bouwresearch (1985) as: resin to which fire retardant substances are added taking in fire retardant groups in the macromolecules which limit the contribution to further fire development and propagation from the surface of the product to classes 1, 2 and 3
The type of resin material itself also plays an important role. Several polymer resins are available, the most common being polyester, vinylester and epoxy. All of these resins have their advantages and disadvantages in comparison to the others. Bouwmeester Advanced Composites B.V. describe these pros and cons of each material, which are displayed in table 5.2.

Resin	Advantages	Disadvantages
Polyester	• Relatively easy to use • Most inexpensive	• Moderate mechanical properties and shrinkage with curing • High styrene emission with open moulds • Limited processing time • Moisture absorption
Vinylester	• Very good chemical properties • Better mechanical properties than polyester	• Generally post-curing is neccesary • High styrene content • Higher costs than polyester • Large shrinkage with curing
Epoxy	• Good chemical and mechanical properties • No toxic emissions • Good moisture absorption resistancy • Relatively longer processing time possibilities • Good material behaviour with high temperatures • Low shrinkage with curing	• Higher costs than vinylester • Mixture is critical for material properties

Table 5.2 | Comparison of material characteristics of polymer resins (Bouwmeester Advanced Composites B.V.)

Judging from the described material characteristics, epoxy seems best suitable due to its mechanical properties, resistance to moisture absorption and good material behaviour with high temperatures. As explained in paragraph x, the mechanical properties are important as well as resistance to moisture absorption as the WE-façade duct is exposed to weather conditions in order to avoid problems such as leakage or moulds. In order to further improve the fire resistance of the resin, optional fire retardant substances are mixed into the resin, examples are halogen containing substances. The only disadvantage is the higher cost of epoxy compared to polyester and vinylester. In paragraph 5.3, the costs of the WE-façade product will be further discussed. Typical FRP panels have a thickness of 3 to 5 mm when combined as a sandwich element.

Aside from the resin material, the type of glass fibre reinforcement influences the material properties in terms of mechanical properties. The most commonly used glass type is E-glass of which three types of glass fibre reinforcements can be distinguished, namely glass mats, a bidirectional square weave and unidirectional weave (Stichting bouwresearch, 1985). With unidirectional weaves the bending strength, compressive strength and tensile strength are significantly higher than the other two options which is of great benefit for the composition of FRP for the duct and its mechanical performance. In addition, the glass fibre content of the composition is significantly higher with unidirectional weaves. These material properties are shown in table 5.1.

With layering of a FRP sandwich element, the core material and especially the coating material influence the material performance and characteristics. The core material has an impact on the fire resistance, moisture absorption resistance and thermal properties of a FRP sandwich element. Aside from the material properties of core materials, also costs should be considered. Mechanical strength is not the most important consideration when choosing a core material as core materials could only slightly improve the final mechanical properties of a sandwich element according to Stichting bouwresearch (1985). The core material is mostly beneficial for layering and attachment of the FRP elements. However, the layering with multiple FRP layers will improve the mechanical properties. Table 5.3 shows the general properties of common core materials.

For the WE-façade the most important considerations for core materials are moisture absorption resistance, fire resistance and weight. Therefore PUR or PIR foams seem most suitable as a core material for the product due to their relatively low weight, high moisture absorption resistance and decent behaviour with higher temperatures. In addition, the FRP layers and the coating material will provide most fire resistance properties of the elements.

For the coating material, the most common applied and suitable topcoat is a gel coat. This gel coat protects the FRP panels from weather influences and discoloration. Typically a topcoat should contain fire retardant substances and pigments. The thickness of the topcoat is typically 0,4 to 0,6 mm. A different option is usage of a foaming topcoat in case of fire which acts as a fire retardant and reduces fire propagation. A foaming topcoat would probably be the safe option for a top coat of the WE-façade in order to protect the building and prevent fire propagation to the building as it is not unlikely that a wind-turbine fails and causes fire.

5.2.6 | Fire safety

Basic regulations for fire safety by the Dutch Building Codes (Bouwbesluit, 2012), state that the class of contribution to fire propagation of material surfaces should at least be class 4. The fire propagation class of FRP could range from 1 to 5. However, solely FRP would easily be class 5. Therefore measurements such as a fire retardant coating and mixture of fire retardant substances to the resin are very important towards fire safety. Such measurements could lead to class 2 or even 1 (Stichting bouwresearch, 1985). As described, firstly the top coat of the FRP

Core material	Mass density kg/m³	Moisture absorption in volume percentage	E-modulus in N/mm³	Allowable temperature limit in °C
PUR hardfoam	40	-	>12	80-100
Pur with clay balls	400	2	>65	80-100
PUR with glassfoam balls	210	-	>40	80-100
PIR-foam	40	5	>9	80-100
PF-foam	40	high	>0,6	80-100
Honeycomb	40	-	-	-
Balsa	200	relatively high	4000	-
PVC-Foam	50	relatively high	>20	80
Coremat	600	2,9	1800	*

** dependent on resin*

Table 5.3 | Material properties of most common core materials for FRP sandwich elements (Stichting Bouwresearch, 1985) material is a foaming topcoat which contains fire retardant substances. The topcoat foams in case of fire and reduces fire propagation. Secondly, fire retardant substances are also added to the FRP mixture to increase its fire resistance. However, it should be examined what the exact mixture for the duct elements should be in order to reach an acceptable class of contribution to fire propagation.

5.3 Costs

With the current chosen variant for elaboration, the ROI period of 5 years as shown in the previous chapter is solely based on the wind-turbine costs and its average yearly energy yield. The turbine costs of the FuturEnergy are 1085 euro and its measured expected average yearly yield is 927 kWh per year. Therefore, its yearly yield is worth 927*0,23 euro per kWh (current price) = 213,21 euro. As investigated in phase one, a ROI period of 5 years is considered most profitable. As the costs of fabrication and construction are not included in this calculation, the ROI will inevitably increase with calculation of the total costs for the WE-façade. However, a system such as the WE-façade is an integrated installation in the building. The 5-year ROI period applies to non-integrated renewable energy systems. With investment in a system such as the WE-façade a longer lifetime of the system components is expected due to its integration in the building as a building component regardless of its system independent characteristic. The minimal expected lifetime of a building varies and depends on the lifetime of the different building components or building layers. Van Nunen (2010) has investigated and established in his thesis that nowadays the average lifespan of a building is expected to be around 120 years in The Netherlands from the construction process to demolition. However, housing corporations on the other hand take into account 50 years as a financial lifespan for buildings according to Van Nunen (2010). The financial lifespan is in this case described as the period of time in which the (financial) benefits exceed the costs. Therefore, 50 years are set as boundary lifespan for the WE-façade and in this case WE-façade is considered a façade component.

A calculation of the maximal allowable manufacturing and construction costs within the ROI-period of the system should include consideration of a 50-year lifespan while a wind-turbine on the other hand is most likely have a shorter lifetime of approximately 15-20 years. This results in replacement of the wind-turbine about 3 times in 50 years. In table 5.4 a calculation is made of the “profits” of the energy yield over the lifespan of the turbine (15 or 20 years) and over the lifespan of the WE-façade product (50 years). These so-called profits are considered as the maximum manufacturing and construction costs for the WE-façade in order to break even and stay within the lifespan period with the ROI-period. The actual profits, after the ROI-period, are also calculated for a total lifespan of 50 years including the maximum allowable costs.

5.4 Fabrication process

The technique of fabrication and material of the moulds, as well as the fabrication process of the FRP plates depends on several factors regarding the required elements properties, namely the shape and size of the FRP elements, the number of units of series, the type, orientation and percentage of glass fibres, the type of core material and requirements regarding quality and dimensional accuracy (Stichting Bouwresearch, 1985).

Generally the fabrication process of FRP elements is split up into four sequential steps;

1 | Fabrication of the moulds
2 | Fabrication of the FRP elements
3 | Combining the FRP components with the core material
4 | The finishing of the elements

1 | Fabrication of the moulds

The WE-façade product is bound to small dimensional changes for implementation in other buildings. Therefore the production of products will generally be of relatively small series. For the case building “Teun” WE-façade is installed on 7 floors, from the 9th floor up to the

Calculation of costs for FuturEnergy wind-turbine							
Lifespan in years	Turbine costs in euros	Number of turbines during lifespan of WE-façade	Total costs for turbines	Energy yield per year in euros (current price €0,23 per kWh)	Total energy yield in euros	Profits in euros within ROI = maximum manufacturing and construction costs	Profits after ROI-period up to 50 years including manufacturing and construction costs in euros
15	1085	1	1085	213,21	3198,15	2113,15	5292,35
20	1085	1	1085	213,21	4264,2	3179,2	6396,3
50	1085	3	3255	213,21	10660,5	7405,5	4226,3

Table 5.4 | Calculation of an estimation of the costs and benefits of the WE-façade combined with the FuturEnergy turbine

15th floor, which requires a number of 7 series of the product components. Instalment on taller buildings such as buildings in larger urban typologies will increase the number of products. However, the series will generally remain relatively small. For such small series of components, several fabrication techniques and type of moulds are suitable, namely the hand-lay-up method, the spray-up method and the injection method (Stichting Bouwresearch, 1985). The hand-lay-up and spray-up method are both described as open mould methods, the injection method is a closed mould method. By closed mould a double sided mould is meant, the FRP plates are smooth on both sides. By an open mould a one sided mould is meant and the FRP plates have a smooth side and a rough side. The most common type of moulds for all three methods are FRP moulds which are shaped by moulds of wood, gypsum, foam or glass. For small series of a few components a wooden mould is sufficient.

***2** | Fabrication of the FRP elements*

As described in step 1, the hand-lay-up method, spray-up method and the injection method are optional techniques for fabrication of small series of FRP elements. For “Teun” the hand-lay-up method or the spray-up method is suitable due to the relatively small series of WE-façade components for the case. For larger series in case of a taller building as explained before, the injection method is more suitable.

Hand-lay-up method

The hand-lay-up method is considered the simplest method and is mostly used as a technique for The hand-lay-up method is particularly suitable for shaping large complex components. First the topcoat is sprayed onto the mould. After curing of the topcoat, the glass reinforcements are placed in the mould and the catalysed resin is poured, brushed or sprayed in the mould. The next step is manually rolling on to the mixture in order to remove trapped air, roll the resin thoroughly into the glass fibres and compact the mixture. If necessary the next layers of glass fibre reinforcement and resin is put onto the first layer of mixture. Manual rolling of the mixture is necessary after each layer. For curing without heat on room temperature, the catalyst in the resin is needed in order to initiate the curing process.

Spray-up method

The spray-up method is similar to the hand-lay-up method. The difference with spray-up method is that the glass fibres and resin mixture are sprayed simultaneously with a spray gun into the mould which already prepared by spraying the topcoat into the mould first as with the hand-lay-up method. Typically the spray gun contains two barrels, one with the resin and the other contains the catalyst for the curing process. The remainder steps of fabrication are the same as with the hand-lay-up method, after spraying the mixture into the mould, the mixture is manually rolled.

Injection method

As mentioned, the injection method is a closed mould method therefore the mould consists of two parts. As with the other methods, the topcoat is firstly sprayed onto the mould. Secondly the glass fibres are placed in the both parts of the mould after which the mould is closed. In case of a sandwich element with a core material, the core material is also placed in the mould. For the third step, the resin is injected into the mould and is spread by under and overpressure in the mould. Finally the curing is initiated. In the mould two openings are present, one for the injection of the resin and the other for suction of air out of the mould. With the injection method, the difficult aspect is dimensional control to control the thickness of the element. In addition, this method requires a larger number of series components of at least a few dozens.

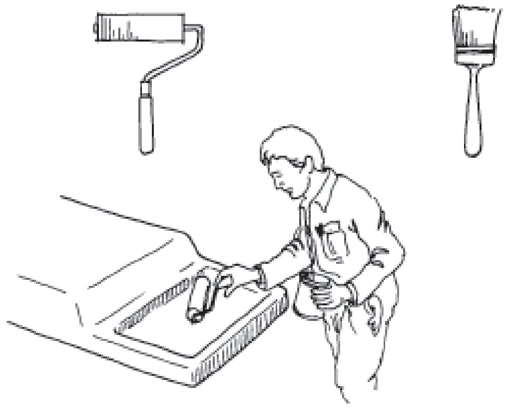


Figure 5.6 | The hand-lay-up method (Stichting Bouwresearch, 1985)

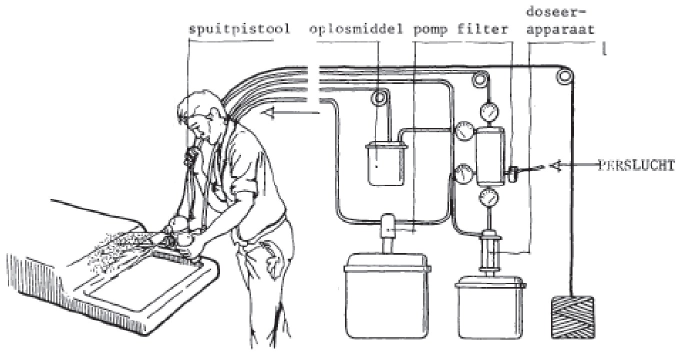


Figure 5.7 | The spray-up method (Stichting Bouwresearch, 1985)

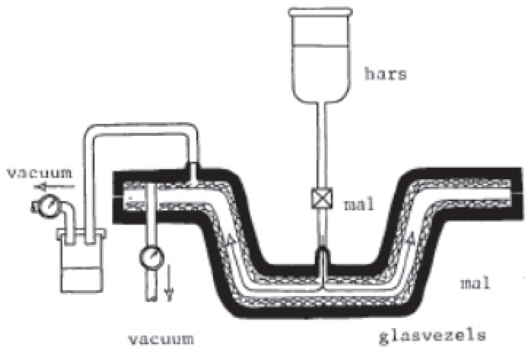


Figure 5.8 | The injection method (Stichting Bouwresearch, 1985)

***3** | Combining the FRP components with the core material*

This step only applies to the hand-lay-up method or the spray-up method as with the injection method the core material is joined with the FRP layers in the mould. After fabrication of the FRP components, the sandwich element is composed by joining the FRP elements with an in advance prepared and shaped core material. The most common method is gluing the parts together. Another possibility is by using a liquid core material which foams while curing and is adhesive to the FRP plates. The method of joining the FRP with the core material is dependent on the type of core material.

***4** | The finishing of the elements*

The final step is finishing of the elements. Often the edges of the components will need finishing as the edges could be frayed. The frayed edges are either sawn or cut (Stichting Bouwresearch, 1985). The cut or sawn edges are then coated with the topcoat. The elements could also need a small repair or extra filling. Finally in order to install or fix the elements, the fixation elements or anchor bolts are added to the element. During this step, it is important to maintain the attachment of the sandwich layers and avoid damage to the topcoat.

5.5 Construction process

The parts and components of the WE-façade are partly dependent on the material properties such as mechanical properties and maximum fabrication dimensions, and partly dependent on the maximum dimensions for transportation of the elements. With FRP elements, larger components maintain their mechanical properties better than smaller components which are joined together. With joined components, the seams and their finishing are utterly important. According to Stichting Bouwresearch (1985), the biggest problem with joining FRP elements is maintaining the fire safety requirements as not correctly finished seams could contribute to fire propagation. Seams should also be correctly finished regarding waterproofing. Therefore, less seams as possible is desired. The maximum dimensions considering transportation are: length 18 m, height 4 m and width 2,5 m.

5.5.1 | WE-façade parts and components

With consideration of the above mentioned issues, the duct of the WE-façade is divided in four elements of FRP each to be fixated to a certain side of the inlets namely the left (1), upper (2), right (3) and lower (4) side as shown in figure 5.8. With 4 duct components the number of seams is kept to a minimum in order to avoid problems with connections. In addition, less components is beneficial for reducing the overall costs for fabrication of the components as less different moulds are needed. The hand-lay-up and spray-up method are very well suited for the fabrication of these large elements. Component 5 is the FRP case shape of the column on the outside and number 6 is the location of the FuturEnergy wind-turbine.

The four components of the duct are fixed with window frame elements at the inlets on both façades similar to the fixation of glass in a window frame. These window frames will maintain the appearance of the windows of the other window openings of the building façades in order to keep the change in appearance to a minimum. The FRP plates of the duct are fixated in the window frame components similar to the fixation of glass in a window frame. Each numbered element in figure 5.9 will be combined with the corresponding window frame component on the side of the inlets. Impressions of the product installed in "Teun" and principle basic connection details are shown in figures 5.10 to 5.14.

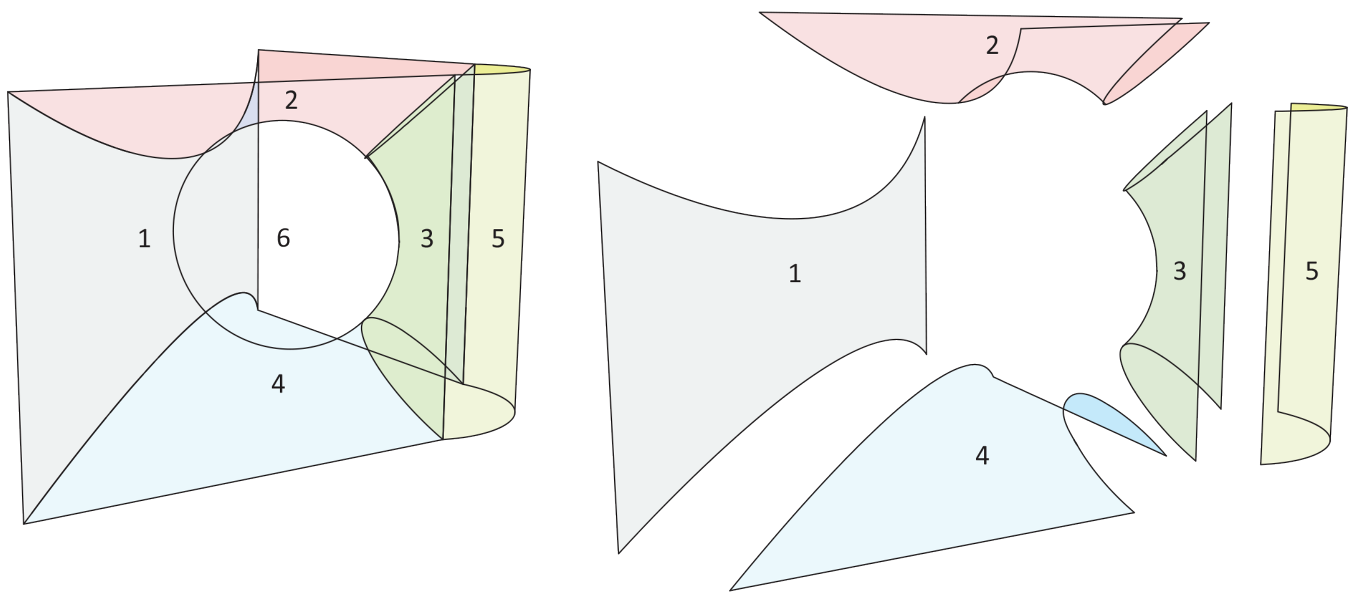


Figure 5.9 | Components of the duct

Impressions of the WE-façade product installed in "Teun"

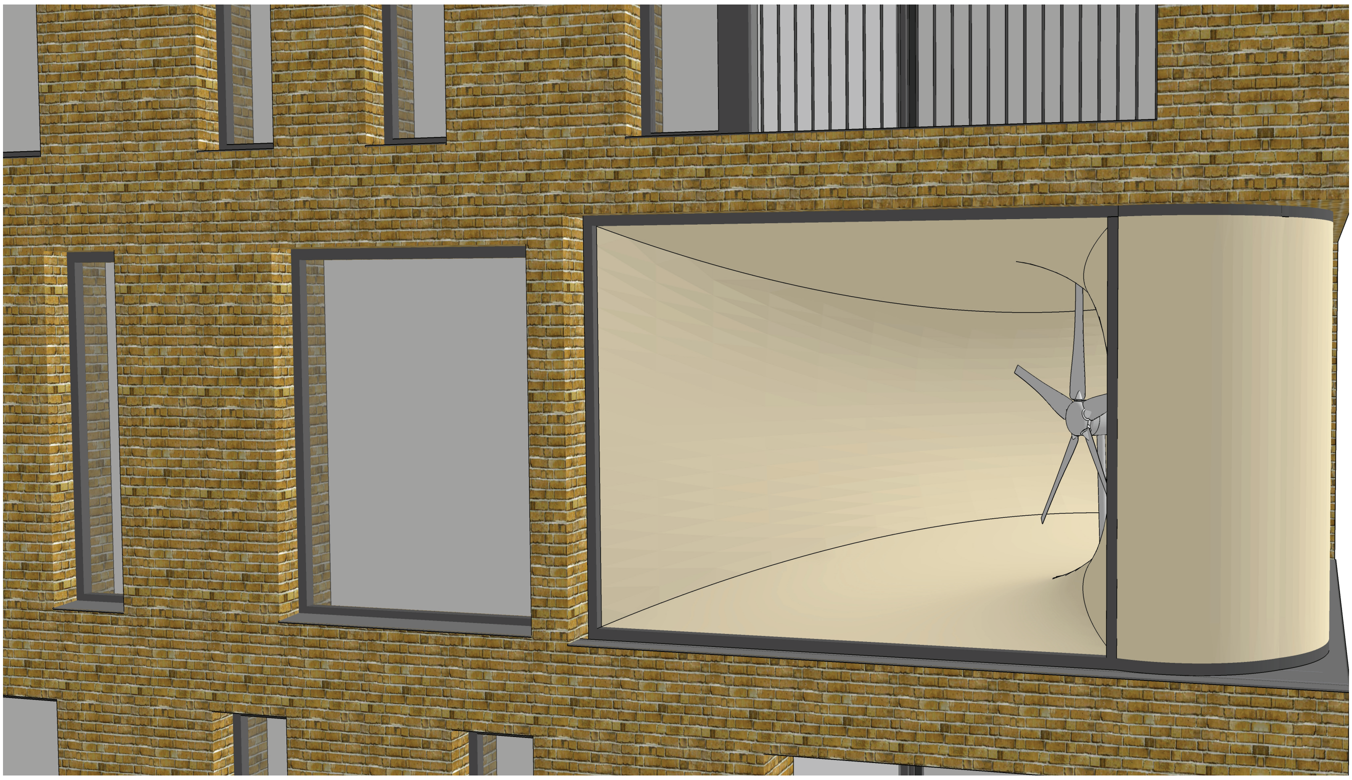


Figure 5.10 | An impression of the installed WE-facade (1)

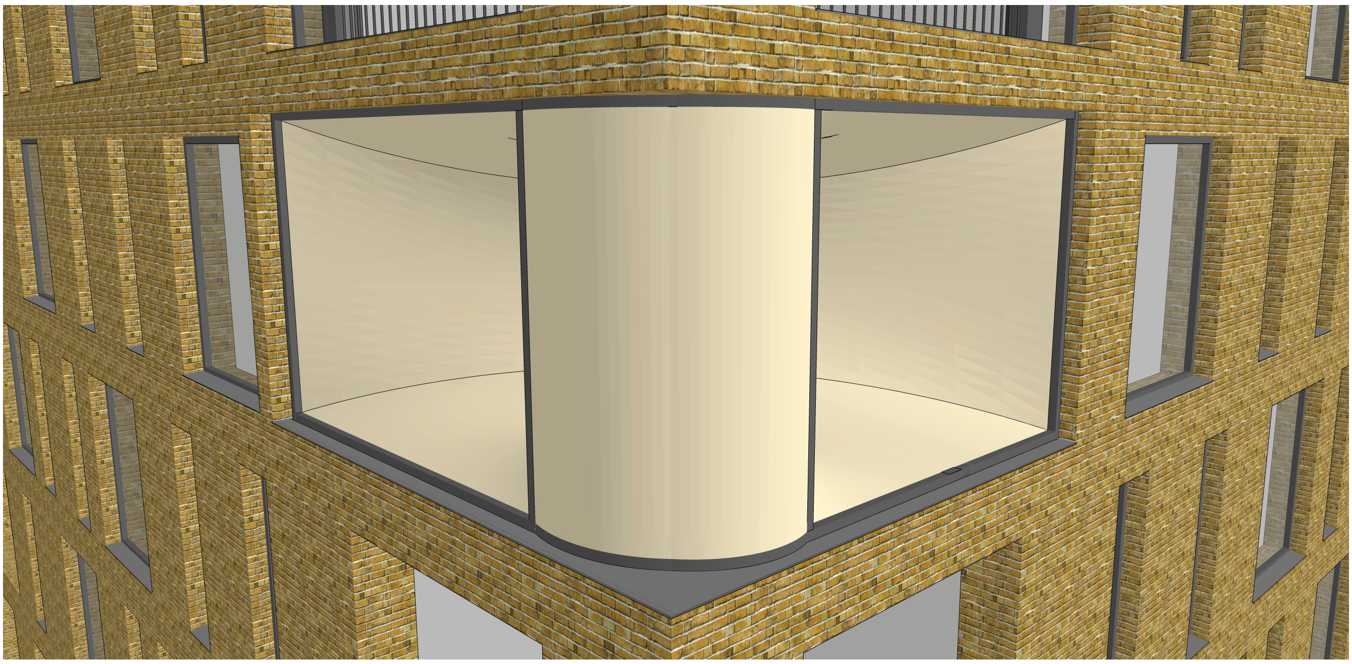


Figure 5.11 | An impression of the installed WE-facade (2)

Principle construction detail 1| V1 | Vertical fixation detail

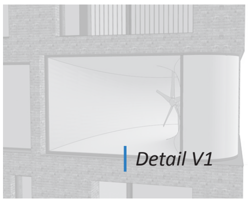
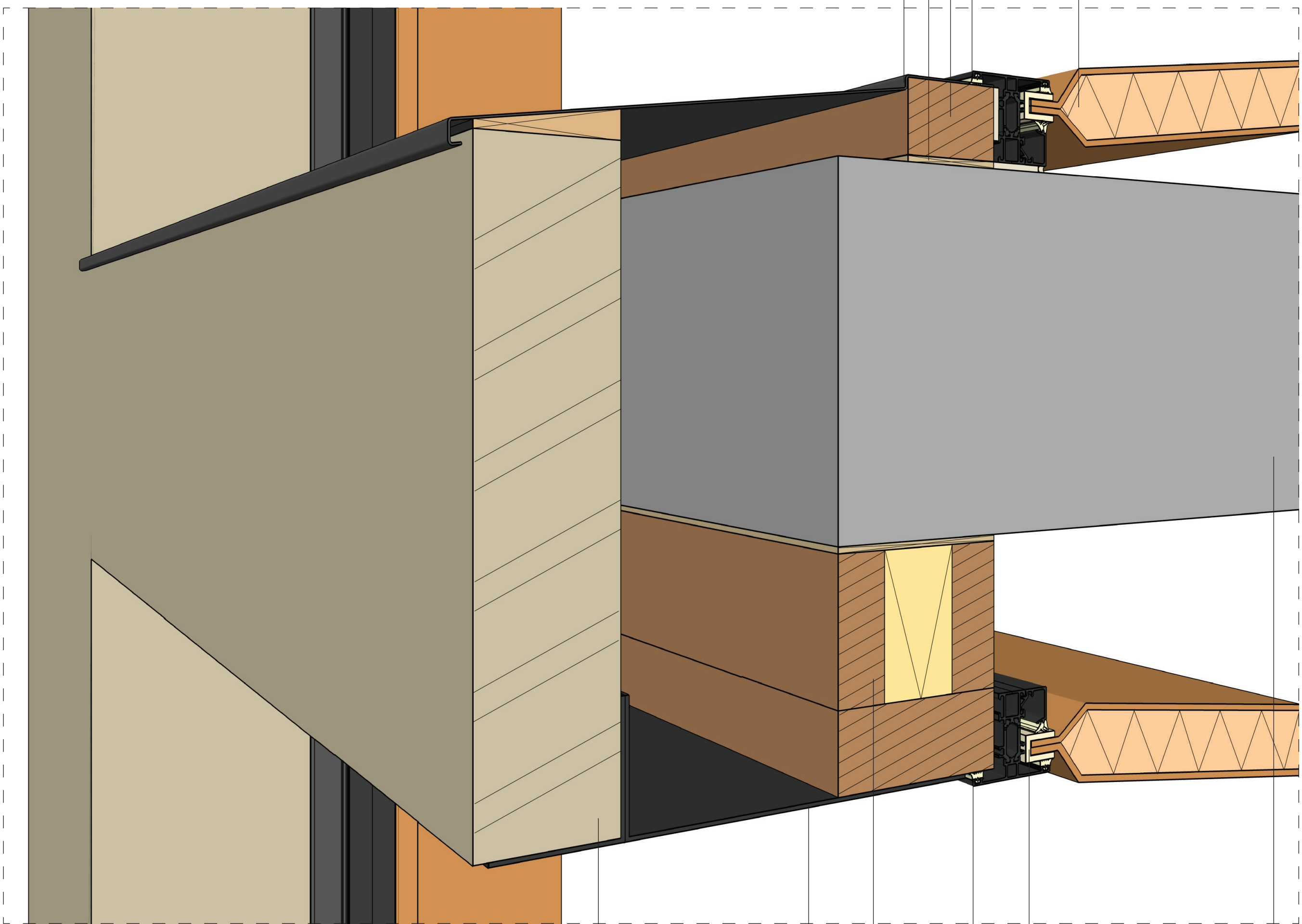


Figure 5.12 | Vertical fixation detail | FRP plate fixation frames to floor



Principle construction detail 2 | H1 | Horizontal fixation detail

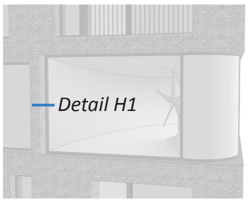
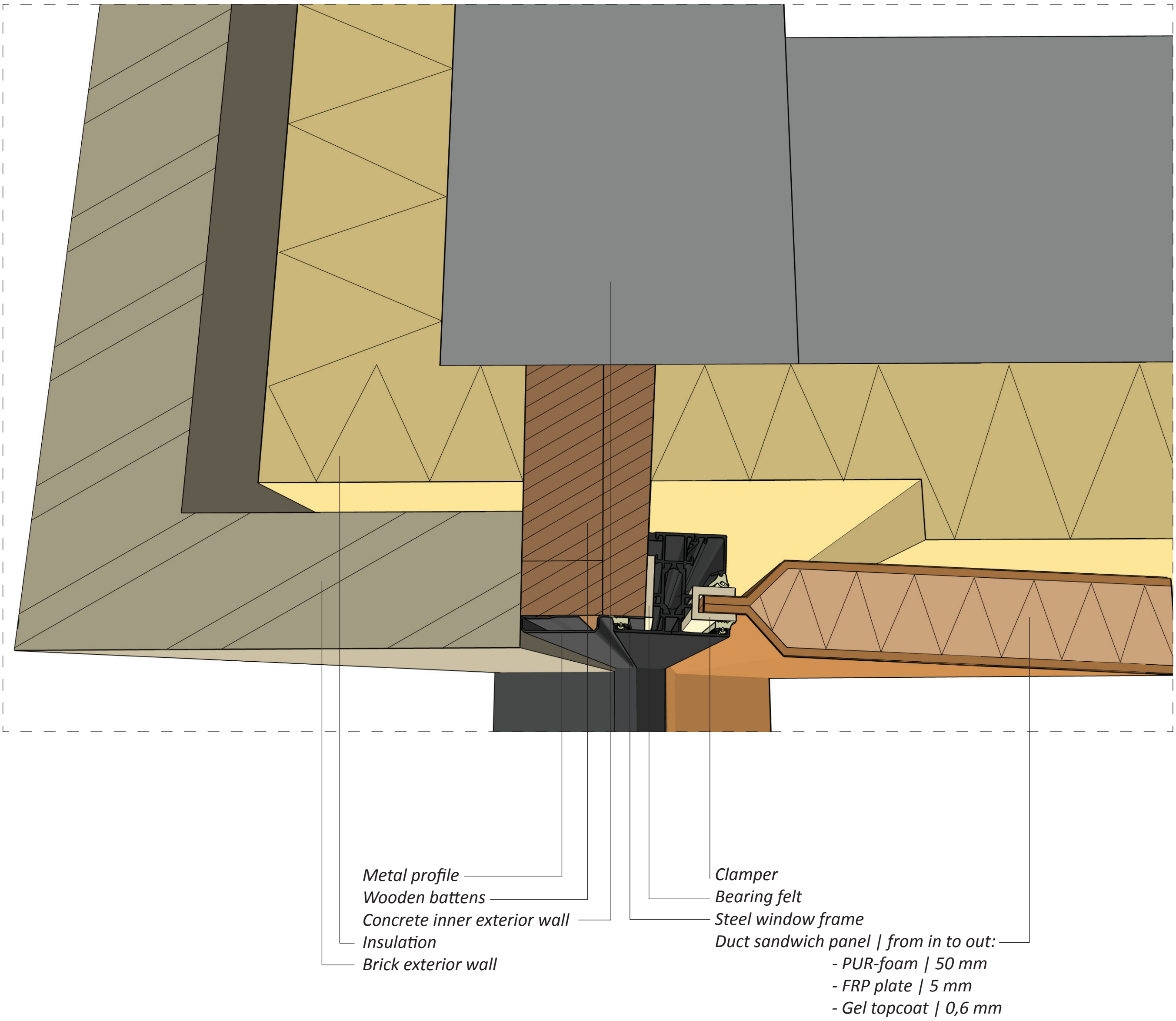


Figure 5.13 | Horizontal fixation detail | FRP plate fixation frames to exterior wall



Principle construction detail 3 | H2 | Horizontal fixation detail

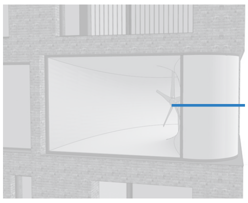
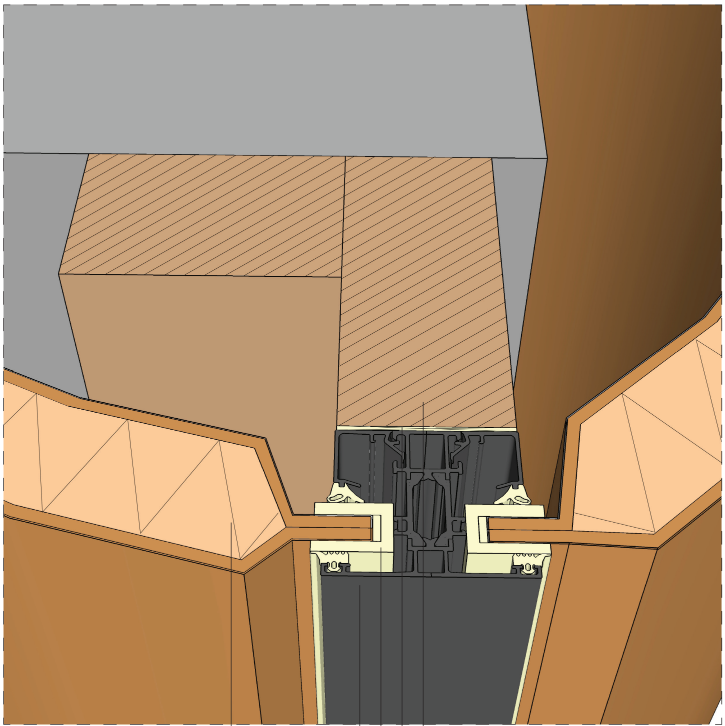


Figure 5.14 | Horizontal fixation detail | FRP plate fixation frames to column



FRP plate number 4 contains an opening at the location of the wind-turbine for the foundation element of the turbine as it is necessary for the turbine forces to be carried off separately by the building construction as a point load due to its weight.

At all connections of FRP to the inlets and around the foundation element of the wind-turbine, sound-damping components are installed. As investigated in phase one, one of the conclusions of the Encraft Warwick Wind Trials Project (2009) was that mostly the installed wind-turbines were switched of due to the noise pollution. It is known that wind-turbines produce mechanic low frequent noise which is in many cases not damped by building façade constructions (RIVM, 2013). As according to RIVM (2013) there are only two guidelines in the Netherlands regarding low frequent sound, these guidelines are not valid legally. However, WE-façade should prevent low frequent noise and noise pollution to the occupants of the building in order to operate successfully.

5.5.2 | Sequence of construction

The construction process of the WE-façade system requires a certain construction sequence. It is assumed that the system will mostly be integrated in new buildings considering the 2020 EU directive as described in chapter 1. With new buildings it is possible to install each WE-façade system with the construction of each building storey. This provides an easier build-up as the large components of the WE-façade are easily lifted on to the corresponding building floor before the start of the build of the next building storey. In many cases, as with “Teun”, the building structure is built first, after which the façade components in case of prefab façade elements are mounted onto the structure. The prefab façade elements provide the opportunity for the window frame components to be mounted during the fabrication process of these elements. In this paragraph the sequence of construction in the case of “Teun” is further described.

Step 1 | The first step includes the construction of the building structure as meant

Step 2 | Secondly the components of the WE-façade are lifted onto the corresponding building storey. With only the building structure up at this point, lifting the product components onto the building should be easiest as the elements are quite large and require quite a large space in order to lift these onto the building.

Step 3 | Step three entails mounting of the building façades onto the building structure as meant.

Step 4 | The foundation of the wind-turbine is mounted in step four before fixation of the duct elements in order to provide right location of the turbine. The duct components have fixation tolerance space when fixating to the window frame.

Step 5 | For step 5, first the lower duct element is fixated to the window frame components of the façade elements. Secondly the wind-turbine is mounted on to its foundation. Mounting the wind-turbine first before the three other duct components provides the opportunity for mounting the wind-turbine from the inside of the building. Also the opening around the foundation of the wind-turbine in the lower duct component should be finished and sealed. Finally the remaining duct components are fixated into the window frame components and joined.

Step 6 | The interior wall elements of the building are built-up for step six.

Figure 5.15 |Construction step 1 (NBU, 2013)

Figure 5.16 | Construction step 2 (NBU, 2013)

Figure 5.17 |Construction step 3 (NBU, 2014)

C6

Conclusions

All in all, the WE-façade product is a successful concept of a small scale generic wind-energy generating product. The product is suitable for application in the most common building shapes, square and rectangular, in urban environments and the design is easily be adapted to fit within different buildings with minor changes to its dimensions. In order to determine the exact performance for a specific case, an investigation is required for the specific situation. The investigation should consist of tests on the energy yield and performance which could be influenced by the building location and surroundings, the average wind profile and statistics of the location, the building orientation, the composition and design of the building façade and the applicable dimensional aspects of the product itself such as the contraction ratio and corresponding curvature. However, for the investigated case building "Teun", the product is definitely suitable, the measured performance of the product is better than expected.

As for this project three variants of the product with different contraction ratios were tested, which corresponds with the theory as proposed by Blocken et al. (2011) that an optimal contraction should exist. As a larger contraction provides a higher acceleration of the wind-flow, the optimal contraction ratio has not been established yet in order to provide the optimum balance between accelerated wind-flow through the duct and the wind-blocking effect. More research is needed in order to determine the optimum contraction ratio. Also the actual performance in terms of average yearly energy yield is also dependent on the currently available wind-turbines. It could well be that in the future new or better performing wind-turbines are introduced which improve the overall energy yield significantly. However, solely judging the performance of the product, it does indeed enhance the turbines performance as the elaborated variant of the product does generate more wind-energy than the chosen turbines in an open field due to the acceleration of the wind-flow in the duct by its design.

The application quantity is dependent on the location and the total building height. Therefore, the fabrication costs which are partly dependent on the components quantity vary. Nevertheless, the WE-façade provides an opportunity for a generic prefab, lightweight, small scale and easily implementable renewable energy source. As the product could be considered a building component or an installation, longer return of investment periods than other small scale after-market solutions should be reasonable considering the overall lifetime of buildings and building components. An exact calculation and elaboration of the fabrication of the product should determine the fluctuation in price and whether a minimum number of products is required to maintain a certain reasonable return of investment period. Also an investigation amongst investors for example should establish a reasonable return of investment period for such a system.

Aside from the advantages of the product, architects or project developers should recognize that the WE-façade system is not implemented without any effects on the building design at all. As the product is indeed generic and fits in to many building corners, the hidden product which maintains the buildings aesthetics and appearance does require a sacrifice of floor area.

In the end, the search and development of a small scale generic wind-energy generating solution could be a successful building product with further elaboration and research on its performance and optimum design in relation to its costs and return of investment period.

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Appendix

A.1 Appendix | Open field testdata for variant 1

Variant 1										
α=-30	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**	**1.6**	**1.7**	**1.8**	**1.9**	**1.10**
α avg.	-3,75	-15,17	-18,88	-19,20	-9,38	-13,28	-12,53	-11,77	-2,78	-5,69
Uref	7,39	7,58	7,03	7,17	7,49	7,09	6,34	6,65	7,01	7,44
Um-837	6,03	4,81	4,46	4,23	5,47	4,77	4,59	5,28	6,36	5,89
Um-708	6,55	5,42	4,90	2,63	6,36	5,27	5,19	5,94	7,01	6,58
Um-avg	6,29	5,12	4,68	3,43	5,92	5,02	4,89	5,61	6,69	6,24
γ-837	0,82	0,63	0,63	0,59	0,73	0,67	0,72	0,79	0,91	0,79
γ-708	0,89	0,72	0,70	0,37	0,85	0,74	0,82	0,89	1,00	0,88
γ-avg.	0,85	0,67	0,67	0,48	0,79	0,71	0,77	0,84	0,95	0,84
α=0	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**	**1.6**	**1.7**	**1.8**	**1.9**	**1.10**
α avg.	4,53	-1,21	-2,36	-8,54	-3,35	-4,00	-6,72	-8,67	-3,47	0,41
Uref	8,14	7,76	7,35	8,06	8,59	8,31	7,99	7,60	7,38	7,83
Um-837	8,13	7,73	7,89	7,69	8,22	8,11	7,85	7,58	7,24	7,70
Um-708	8,30	8,12	8,20	8,15	8,36	8,21	8,20	7,87	7,89	8,06
Um-avg	8,22	7,93	8,05	7,92	8,29	8,16	8,03	7,73	7,57	7,88
γ-837	1,00	1,00	1,07	0,95	0,96	0,98	0,98	1,00	0,98	0,98
γ-708	1,02	1,05	1,12	1,01	0,97	0,99	1,03	1,04	1,07	1,03
γ-avg.	1,01	1,02	1,09	0,98	0,97	0,98	1,00	1,02	1,03	1,01
α=30	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**	**1.6**	**1.7**	**1.8**	**1.9**	**1.10**
α avg.	24,74	29,40	23,55	25,06	23,62	27,78	31,75	25,70	23,64	24,46
Uref	8,12	8,65	8,09	8,10	8,09	7,87	7,62	8,18	8,03	8,13
Um-837	7,84	6,55	7,81	7,25	7,02	6,57	6,33	7,36	7,55	7,49
Um-708	8,36	8,35	8,33	8,33	8,33	8,30	8,38	8,36	8,37	
Um-avg	8,10	7,45	8,07	7,79	7,68	7,44	7,36	7,86	7,96	
γ-837	0,97	0,76	0,97	0,90	0,87	0,83	0,83	0,90	0,94	0,92
γ-708	1,03	0,97	1,03	1,03	1,03	1,05	1,10	1,02	1,04	
γ-avg.	1,00	0,86	1,00	0,96	0,95	0,94	0,97	0,96	0,99	
α=60	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**	**1.6**	**1.7**	**1.8**	**1.9**	**1.10**
α avg.	62,91	58,10	57,98	58,68	59,98	62,09	54,74	55,54	54,45	
Uref	8,86	9,44	9,06	9,04	8,84	8,80	8,84	8,31	8,65	
Um-837	1,94	2,73	2,79	2,61	2,25	2,24	2,85	2,87	3,12	
Um-708	5,62	7,52	7,62	7,22	6,88	6,36	7,83	7,91	6,72	
Um-avg	3,78	5,13	5,21	4,92	4,57	4,30	5,34	5,39	4,92	
γ-837	0,22	0,29	0,31	0,29	0,25	0,25	0,32	0,35	0,36	
γ-708	0,63	0,80	0,84	0,80	0,78	0,72	0,89	0,95	0,78	
γ-avg.	0,43	0,54	0,57	0,54	0,52	0,49	0,60	0,65	0,57	
α=90	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**	**1.6**	**1.7**	**1.8**	**1.9**	**1.10**
α avg.	104,88	99,69	95,58	101,10	102,05	107,67	105,06	101,18	100,04	101,71
Uref	8,34	8,30	9,61	9,16	9,09	8,91	8,49	9,27	9,43	10,02
Um-837	2,58	3,39	3,36	3,45	3,32	3,04	3,27	3,21	3,33	3,36
Um-708	2,61	3,86	3,92	3,42	3,81	3,36	3,60	3,73	3,60	3,76
Um-avg	2,60	3,63	3,64	3,44	3,57	3,20	3,44	3,47	3,47	3,56
γ-837	0,31	0,41	0,35	0,38	0,37	0,34	0,39	0,35	0,35	0,34
γ-708	0,31	0,47	0,41	0,37	0,42	0,38	0,42	0,40	0,38	0,38
γ-avg.	0,31	0,44	0,38	0,38	0,39	0,36	0,40	0,37	0,37	0,36

A.2 Appendix | Open field testdata for variant 2

Variant 2										
α=-30	**2.1**	**2.2**	**2.3**	**2.4**	**2.5**	**2.6**	**2.7**	**2.8**	**2.9**	**2.10**
α avg.	4,41	6,97	7,66	-0,91	-0,15	-5,15	-5,93	-4,50	-0,90	-2,78
Uref	7,96	7,61	6,93	6,91	7,14	7,34	7,98	7,75	7,93	6,85
Um-837	7,11	7,74	6,77	5,56	5,74	4,41	5,16	5,64	6,67	5,54
Um-708	7,10	7,61	6,81	5,64	5,69	4,23	5,19	5,72	6,53	5,52
Um-avg	7,11	7,68	6,79	5,60	5,72	4,32	5,18	5,68	6,60	5,53
γ-837	0,89	1,02	0,98	0,80	0,80	0,60	0,65	0,73	0,84	0,81
γ-708	0,89	1,00	0,98	0,82	0,80	0,58	0,65	0,74	0,82	0,81
γ-avg.	0,89	1,01	0,98	0,81	0,80	0,59	0,65	0,73	0,83	0,81
α=0	**2.1**	**2.2**	**2.3**	**2.4**	**2.5**	**2.6**	**2.7**	**2.8**	**2.9**	**2.10**
α avg.	2,72	17,25	17,21	14,43	7,59	0,53	-3,14	0,89	-4,18	-3,79
Uref	7,44	7,16	7,33	6,55	6,38	6,24	7,04	6,89	7,25	7,08
Um-837	8,84	7,82	7,76	7,58	7,51	7,38	7,99	7,65	8,20	8,13
Um-708	8,15	7,85	7,75	7,70	7,48	7,34	7,79	7,51	8,08	8,03
Um-avg	8,50	7,84	7,76	7,64	7,50	7,36	7,89	7,58	8,14	8,08
γ-837	1,19	1,09	1,06	1,16	1,18	1,18	1,13	1,11	1,13	1,15
γ-708	1,10	1,10	1,06	1,18	1,17	1,18	1,11	1,09	1,11	1,13
γ-avg.	1,14	1,09	1,06	1,17	1,17	1,18	1,12	1,10	1,12	1,14
α=30	**2.1**	**2.2**	**2.3**	**2.4**	**2.5**	**2.6**	**2.7**	**2.8**	**2.9**	**2.10**
α avg.	36,91	35,36	35,63	31,47	30,92	38,30	29,50	26,44	27,65	29,54
Uref	9,24	8,85	9,19	9,20	9,23	8,88	8,06	8,51	8,80	8,14
Um-837	6,16	6,35	6,14	7,40	7,55	8,01	7,34	7,63	7,22	7,50
Um-708	8,13	8,23	8,08	8,36	8,32	8,28	8,38	8,20	8,27	
Um-avg	7,15	7,29	7,11	7,88	7,94	8,15	7,86	7,92	7,75	
γ-837	0,67	0,72	0,67	0,80	0,82	0,90	0,91	0,90	0,82	0,92
γ-708	0,88	0,93	0,88	0,91	0,90	0,93	1,04	0,96	0,94	
γ-avg.	0,77	0,82	0,77	0,86	0,86	0,92	0,98	0,93	0,88	
α=60	**2.1**	**2.2**	**2.3**	**2.4**	**2.5**	**2.6**	**2.7**	**2.8**	**2.9**	**2.10**
α avg.	67,70	74,74	75,59	74,67	67,65	70,24	124,52	76,78	75,13	76,53
Uref	8,70	8,68	8,99	8,52	8,77	9,33	9,46	8,79	9,11	9,57
Um-837	2,29	1,76	1,93	2,05	1,74	1,65	1,66	1,94	2,02	2,14
Um-708	3,13	2,24	2,45	2,49	2,28	2,03	1,97	2,32	2,41	2,71
Um-avg	2,71	2,00	2,19	2,27	2,01	1,84	1,82	2,13	2,22	2,43
γ-837	0,26	0,20	0,21	0,24	0,20	0,18	0,18	0,22	0,22	0,22
γ-708	0,36	0,26	0,27	0,29	0,26	0,22	0,21	0,26	0,26	0,28
γ-avg.	0,31	0,23	0,24	0,27	0,23	0,20	0,19	0,24	0,24	0,25
α=90	**2.1**	**2.2**	**2.3**	**2.4**	**2.5**	**2.6**	**2.7**	**2.8**	**2.9**	**2.10**
α avg.	102,29	103,34	108,53	110,12	101,34	104,06	105,04	96,72	100,54	102,28
Uref	9,42	9,14	8,56	8,41	8,37	8,61	8,97	8,95	9,04	8,86
Um-837	3,94	3,61	3,29	3,22	3,31	3,53	3,76	3,80	3,50	3,24
Um-708	4,16	3,85	3,95	3,58	3,78	3,73	3,92	3,93	3,95	3,68
Um-avg	4,05	3,73	3,62	3,40	3,55	3,63	3,84	3,87	3,73	3,46
γ-837	0,42	0,39	0,38	0,38	0,40	0,41	0,42	0,42	0,39	0,37
γ-708	0,44	0,42	0,46	0,43	0,45	0,43	0,44	0,44	0,44	0,42
γ-avg.	0,43	0,41	0,42	0,40	0,42	0,42	0,43	0,43	0,41	0,39

A.3 Appendix | Open field testdata for variant 3

Variant 3										
α=-30	**3.1**	**3.2**	**3.3**	**3.4**	**3.5**	**3.6**	**3.7**	**3.8**	**3.9**	**3.10**
α avg.	-23,27	-24,96	-28,01	-24,62	-29,24	-22,22	-21,07	-25,07	-25,01	-23,23
Uref	6,92	7,10	6,30	6,62	6,71	6,22	6,55	6,25	6,41	6,80
Um-837	5,39	5,46	4,95	5,83	4,96	5,50	5,76	4,06	5,19	6,05
γ-837	0,78	0,77	0,79	0,88	0,74	0,88	0,88	0,65	0,81	0,89
α=0	**3.1**	**3.2**	**3.3**	**3.4**	**3.5**	**3.6**	**3.7**	**3.8**	**3.9**	**3.10**
α avg.	1,65	-7,43	-4,70	-7,09	-5,04	-3,74	-6,99	-2,38	-6,60	-4,04
Uref	6,58	6,85	7,08	6,72	7,47	6,88	7,17	6,93	6,71	8,03
Um-837	6,95	7,88	7,49	7,32	8,13	7,51	7,83	7,16	7,58	8,12
γ-837	1,06	1,15	1,06	1,09	1,09	1,09	1,09	1,03	1,13	1,01
α=30	**3.1**	**3.2**	**3.3**	**3.4**	**3.5**	**3.6**	**3.7**	**3.8**	**3.9**	**3.10**
α avg.	32,24	30,55	32,76	32,48	32,61	28,94	31,11	30,33	33,06	33,85
Uref	7,97	7,69	8,07	7,90	7,39	7,53	7,39	8,03	7,56	7,51
Um-837	8,26	8,34	8,32	8,01	8,13	8,14	8,30	8,28	8,21	8,02
γ-837	1,04	1,08	1,03	1,01	1,10	1,08	1,12	1,03	1,09	1,07
α=60	**3.1**	**3.2**	**3.3**	**3.4**	**3.5**	**3.6**	**3.7**	**3.8**	**3.9**	**3.10**
α avg.	62,20	52,82	53,82	56,78	56,96	52,74	55,43	56,66	55,36	55,05
Uref	8,38	7,99	8,45	8,42	7,99	7,66	8,19	7,50	8,01	8,01
Um-837	3,50	5,53	5,29	5,48	5,40	5,93	5,64	4,86	5,55	5,50
γ-837	0,42	0,69	0,63	0,65	0,68	0,77	0,69	0,65	0,69	0,69
α=90	**3.1**	**3.2**	**3.3**	**3.4**	**3.5**	**3.6**	**3.7**	**3.8**	**3.9**	**3.10**
α avg.	88,39	89,84	88,78	86,69	87,04	92,41	90,55	84,94	87,21	82,93
Uref	7,78	7,77	7,52	7,41	7,78	8,20	7,65	7,70	7,55	8,12
Um-837	3,02	3,09	2,99	2,56	3,08	3,67	2,99	2,72	2,12	2,49
γ-837	0,39	0,40	0,40	0,35	0,40	0,45	0,39	0,35	0,28	0,31