Weathering of Untreated Timber Facades in the North Netherlands

Research Report // Lada Leidmane

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Weathering of Untreated Timber Facades in the North Netherlands
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1. Introduction

1.1. Problem Statement

Research Question: How do different design aspects influence the weathering of untreated timber facades in the distinct climate and environmental conditions of the North Netherlands, and what are the resulting effects on building appearance?

The use of wood has always played an essential role in our interaction with the environment. It is an integral part of the natural world, which we have been employing for various purposes such as shelter, fuel and tools. Wood is one of the oldest building materials, resulting in a "form of construction from which all later forms took their lead" (Herzog et al., 2004, p. 24). Being a very flexible and widely used building material, untreated wood, however, is very sensitive to solar radiation and precipitation. Wooden facades exposed to weather often change their colour and pattern. The overall term for weather-caused changes on the surface of the material is weathering (Hirche, 2014).

Untreated timber facades are exterior cladding in wood which does not undergo any kind of treatment before or after its installation. Wood treatment or impregnation with chemical preservatives improves its resistance to wood-decay fungi and insects. It is important to understand, however, that most impregnation agents contain toxic substances which are hazardous to human health and the environment (Zimmer et al., 2020, p.13). Even though nowadays we witness the development of biocide-free (non-toxic) wood protection systems (Zimmer et al., 2020, p.13), this study focuses on the timber cladding used in its natural form.

While weathering, in a broader term, means the breakdown and dissolution of materials, it should not be confused with a destructive process of material decay (Hirche, 2014). Hirche brings to attention the fact that most of the research in timber weathering is done by forestry or building research institutes. A commonly shared perspective among researchers in the field is that weathering is mainly regarded as undesired as it results in material vulnerability and is aesthetically problematic.

The objective of the research, however, aligns with recent studies conducted at Aalto University, the Norwegian University of Science and Technology and the Norwegian Institute of Bioeconomy Research (NIBIO) (Herche, 2014; Fajer, 2022; Zimmer et al., 2020). Together, these works aim to change the perception of wood weathering as a positive rather than negative aspect by providing information on possible predictions of wood colouration and the influence of the building's overall design on the weathering outcome. Similar to these researches, this study addresses the gap in architectural practice in understanding and using wood weathering to our benefit in the design process.

In contrast to previously conducted research on timber weathering mentioned above, this study explores the topic in the context of the Netherlands, where the timber tradition is less strong than in Nordic countries. Therefore, this research focuses on translating the existing findings on wood weathering and possible benefits for building design character into Dutch conditions such as temperate climate, external timber supply and lack of local precedents implementing untreated timber for exterior cladding.

1.2. Context: Timber Architecture in The Netherlands

Similar to the situation in many European countries, timber once used to be one of the most common construction materials in the Netherlands. The tradition of building in timber gradually declined around the 15th-16th centuries and has been subsequently lost (van Tussenbroek, 2017). New building regulations following the 1421 and 1452 city fires in Amsterdam, the overspreading of brick construction and the lack of local timber resources were the main factors contributing to the disappearance of timber construction (Verschoor, 2023).

With the contemporary agenda for sustainable building, which advocates for the reduction of greenhouse gas emissions and an increase in the use of renewable building materials, timber is an excellent alternative to other materials contributing to the pollution of the environment. In 2021, the Metropolitan Region of Amsterdam (MRA) signed the Green Deal Timber Construction covenant. That means that all new construction has to include at least 20% timber/biobased materials (AIAMS, 2021). Increasing timber use in buildings naturally leads to increased timber application as a facade material. It is, therefore, beneficial for future facade designs to understand the opportunities and limitations untreated timber provides.

Several contemporary Dutch architectural firms, including Marc Koehler Architects and Julius Taminiau Architects, have presented untreated timber facade designs in recent years. Their projects, located in diverse rural and urban contexts, indicate an emergent interest in the natural weathering of timber. Nevertheless, initial research suggests that these endeavours are presently regarded as experimental rather than conventional architectural approaches.

Although generally, we witness an advancement in timber construction technologies, with spans getting longer and buildings higher, timber often stays primarily a structural material, which is concealed from the outside. There is a general lack of studies regarding timber usage in building envelopes, which results in undesired weathering outcomes or avoidance of timber external application. The research of timber weathering in the context of the Netherlands' climate and local environment can contribute to its broader and smarter use as a cladding material.

1.3. Theoretical Framework

This study bridges the fields of wood architecture and design with wood technology, which includes disciplines like wood anatomy, biology, chemistry, physics, and mechanical technology. Consequently, both architectural and scientific viewpoints are essential for providing the theoretical framework. This research is built upon three important studies on timber weathering in architecture conducted in the Nordic region over the last decade.

The earliest work in this research sequence is the PhD thesis by M. Hirche (2014), which explores the possibilities of predicting precise wood colouration changes resulting from wood weathering depending on timber cladding patterns. The research provides detailed results on the weathering of pine wood facade samples in Trondheim weather conditions. To the best of the author's knowledge, Hirche's work is the first peer-reviewed scientific work contributing to the subject of wood cladding and facade weathering. Prior knowledge in this area is based solely on experience from the weathering of timber facades and lacks a research foundation (Hirche, 2014, p. 19).

Fajer's Master's thesis (2022) examines the potential effects of weathering on the facade of the building in relation to its overall design, including building orientation, ornaments, windows, gutters and eaves. By analysing selected architectural examples, the study explores the possibilities of integrating timber weathering in the architectural design process using 3D simulations that account for solar radiation and wind patterns. Notably, Fajer's research, while comprehensive, does not account for the influence of precipitation on timber weathering. This limitation may necessitate caution when applying the findings to climatic conditions in the Netherlands.

The report authored by Zimmer et al. (2020) from the Norwegian Institute of Bioeconomy Research (NIBIO) represents a collaborative effort involving researchers from the fields of wood technology, forestry, and architecture. This research publication aims to function as an informative and instructive resource for a diverse audience, including architects, craftsmen, manufacturers, homeowners, and anyone with a vested interest in the application of unpainted wooden claddings.

Unlike the study conducted by Hirche and Fajer, the NIBIO paper primarily focuses on unpainted wooden facades, encompassing case studies that involve facades constructed from both modified and treated wood. It is crucial to emphasize that, as highlighted by Zimmer et al. (2020, p. 5), treated or modified wooden facades experience a comparable ageing process. Notably, the chapter 2.6. Wood Treatment in current research is exploring environmentally friendly wood treatment methods. However, aligning with the perspective of Hirche and Fajer, this study deliberately omits the discussion of treated wood from its main discourse to avoid potential confusion.

1.4. Methodology

W O O D + D E S I G N + W E A T H E R + T I M E = W E A T H E R I N G

(Hirche, 2014, p. 37)

In the equation, Hirche (2014) identifies four key factors affecting weathering in timber architecture: wood type, cladding design, in-situ weather conditions, and exposure time. Experimental research, according to Hirche, is an effective approach to understanding the impact of each variable on weathering. Experimentation involves methods which resemble conditions in the built context while allowing for a thorough assessment of a specific weathering factor.

Hirche's study (2014) proves that experimental research can reveal more accurate and informative results for specific weather conditions than the general "rules of thumb" presented in building guidelines. For example, Voll's experiments, showed faster and more uniform grey colour development on West-facing samples, contrary to literature suggestions for North-facing samples (Hirche, 2014, p.199).

The primary limitation of experimental research in timber weathering is the time aspect. Likely, experiments with samples exposed to weathering just for a few weeks would give very limited information, which would not be enough to make certain conclusions. An alternative research method would be the analysis of several case studies in the context of the North Netherlands. The preliminary research, however, indicated the general shortage of untreated timber use for external cladding in the study area, which did not allow for further development of a later approach as the primary research method.

Taking into account the limitations mentioned above, the research was mainly carried out through the available literature on the timber weathering process. The objective is to translate the existing research in timber weathering in the architectural field in Nordic countries (Hirche, 2014; Fajer, 2022) into the context of the North Netherlands. This allows us to understand the opportunities and limitations the weathering process can provide for the aesthetics of timber buildings in this area (see 5.1. Design Strategies).

The primary part of the research involves contextualising existing experimental and case study research to the local climate. The weather conditions in the North Netherlands, specifically the Lauwersoog and Groningen regions were studied. Those were documented in weather maps to provide a complete overview of winds, precipitation and sun hours over the year (see 3.2. Climate Studies). As climate is a critical factor in timber weathering, this is a crucial tool in revealing the main points of interest regarding the weathering process in specific in-situ conditions.

Compared to the independently positioned timber cladding elements analysed by Hirche, wooden facade components usually face a more intricate physical context. Factors such as thermal bridges, electrical and other installations, facade openings, projecting architectural elements, nearby vegetation, human activity, and construction methods collectively influence the weathering process. These variables can significantly affect how facade elements are exposed to weather conditions, leading to alterations in colour and pattern due to weathering. Therefore, this research also aims to identify and discuss the key environmental factors elucidated in Fajer's (2022) and Zimmer et al. (2020) studies that need to be considered when comprehending timber weathering. These findings are presented in section 4.3. Architectural Design and Detailing and 5.2. Design Strategies.

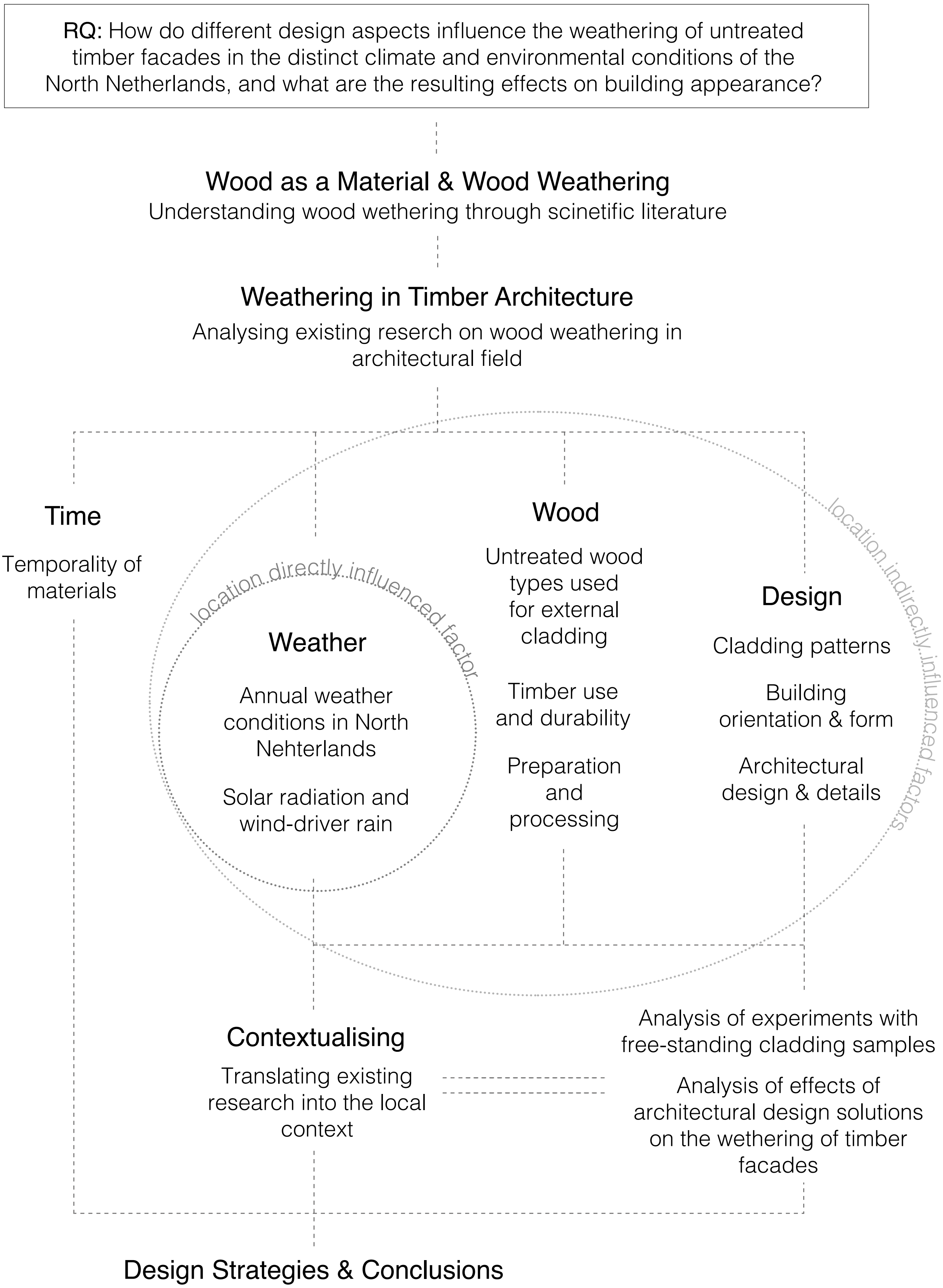


Fig. 1. Methodology diagram. Created by the author.

2. Wood as a Material

Wood stands out as an exceptionally versatile material, facilitating its extensive utilization across various applications. The weathering process of wood is influenced by a combination of its inherent qualities, contingent upon the specific tree species, as well as characteristics acquired through certain wood processing methods. This chapter aims to provide a comprehensive overview of terms, qualities, and classifications of wood that hold significance in the context of the weathering phenomenon.

2.1. Wood Structure and Composition

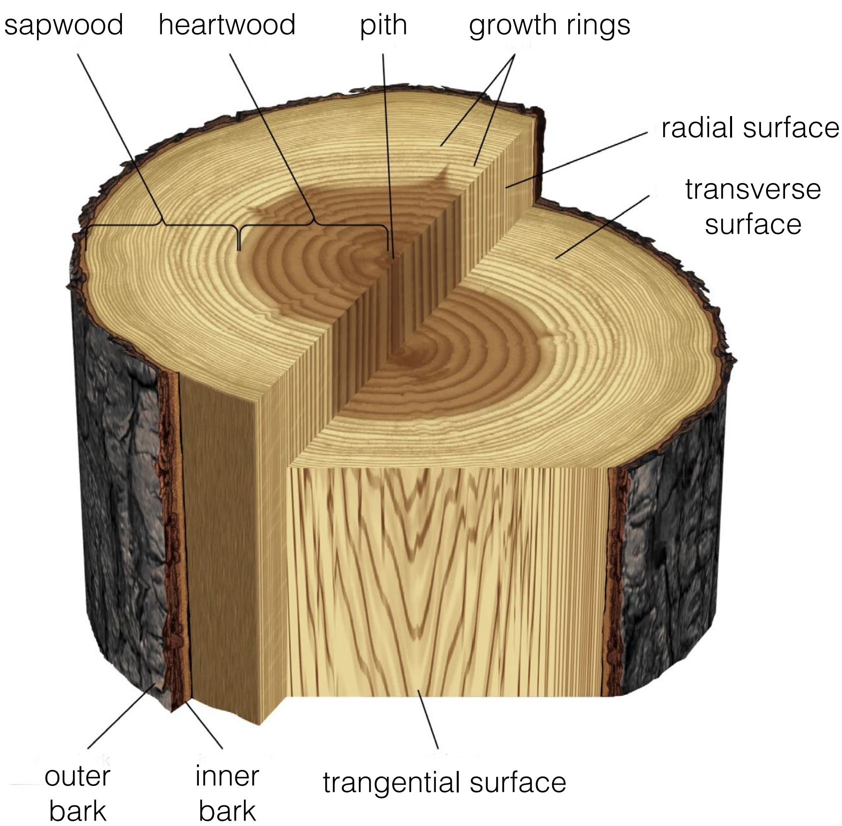


Fig. 2. Anatomy of a tree trunk. From "Britannica", by G. T. Tsoumis, n.d. (https://www.britannica.com/science/wood-plant-tissue/Wood-as-a-material).

The primary reservoir of wood for construction purposes is derived from the tree trunk. In a transverse section, the tree trunk comprises three principal components: the pith, wood, and bark. The wood itself is composed of concentric layers recognized as growth rings or annual rings. The distinctive texture of timber materials is predominantly shaped by the patterns formed by these annual rings. The outer section of wood, usually lighter in colour, is the vital, living segment responsible for the transportation and storage of water and nutrients. As the tree grows, the innermost region stops actively participating in a tree's life processes. The inner section of the tree trunk, known as heartwood, consists of dead, hollow cells and is characterized by a darker colour. This portion, being drier and denser, is more durable as a construction material (Tsoumis, n.d.).

2.2. Wood Species

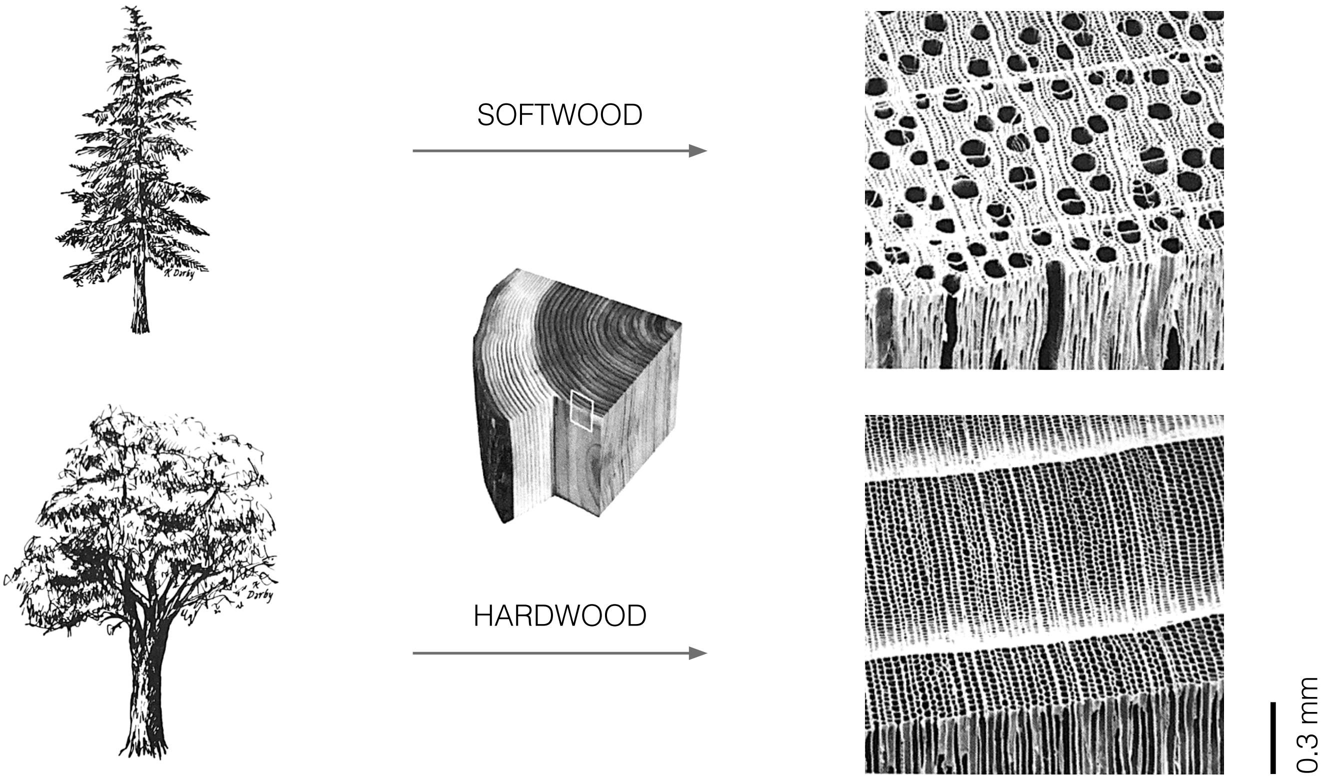


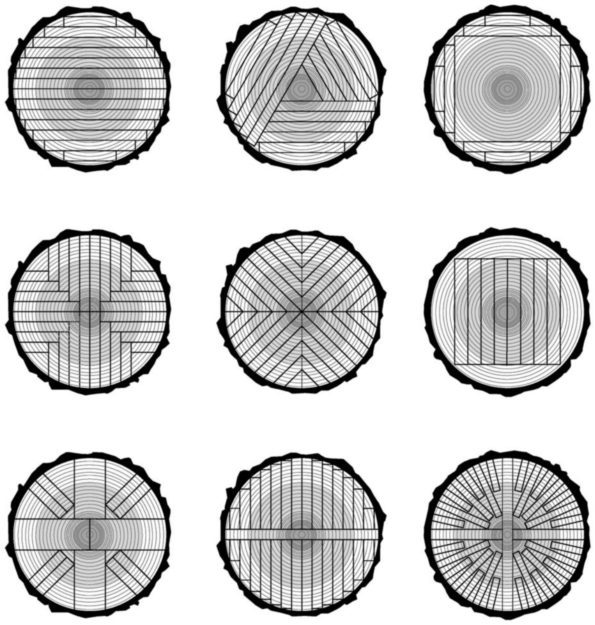
Fig. 3. Softwood and Hardwood. From *"The Chemistry of Solid Wood"*, by American Chemical Society, 1984.

Wood is sourced from two broad plant categories recognized in commerce as softwoods and hardwoods (Fig. 3). It's important to note that these general designations may not consistently reflect the actual physical hardness or density of all woods. For instance, certain softwoods like Douglas fir and southern yellow pines exhibit notable hardness, while some hardwoods such as yellow buckeye, aspen, and cottonwood are comparatively soft. Despite these exceptions, the terms softwoods and hardwoods are generally applicable to many woods within their respective categories, providing practical designations for the two primary classes of commercial timbers (Rowell, 1984a).

In the Netherlands, various wood species are used for facades, depending on factors such as aesthetics, durability, and sustainability. The most common wood species used untreated for facade cladding are the ones with natural resistance to decay and insects. Western red cedar, European oak, Siberian larch and Redwood are the wood species with good natural durability.

Other types of wood such as Radiata pine are commonly treated to enhance their durability and stability. Thermally modified wood and Accoya wood while not specific wood species are among the most widely used treated wood types for facade cladding. Some researchers including Zimmer et al. (2020) and Fajer (2022) study the weathering of those treated wood types together with untreated wood as they are used in unpainted wooden facades and usually undergo the same changes of the surface as untreated wood when exposed to the external environment. Section 3.4 Treatment of Timber Facades provides more information on the subject of timber treatment.

2.3. Preparation and Production



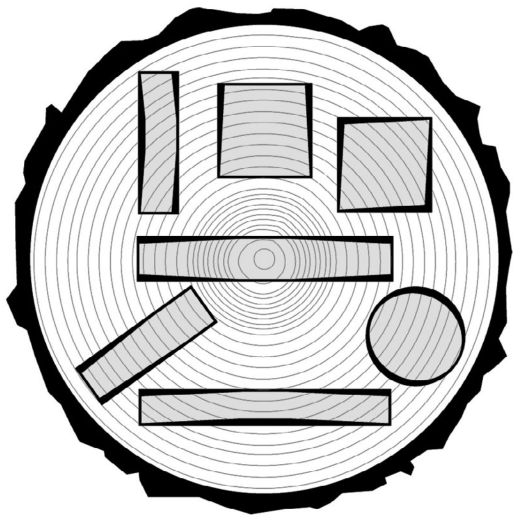


Fig. 4. (left) How tree trunks are cut to produce wood with different appearances and uses. From *"Archdaily"*, by Jose Tomas Franco, 2019 (https://www.archdaily.com/894449/how-tree-trunks-are-cut-to-produce-wood-with-different-appearances-and-uses).

Fig. 5. (right) Shrinkage and distortion of wood upon drying. From *"Archdaily"*, by Jose Tomas Franco, 2019 (https://www.archdaily.com/894449/how-tree-trunks-are-cut-to-produce-wood-with-different-appearances-and-uses).

The preparation and processing of wood are important factors determining the appearance and service of the facade. The look of the cladding is affected by multiple choices one has to make at different stages of wood processing. They include the choice of wood tissue, number and size of knots, fibre orientation, cutting pattern, annual ring width and orientation, drying process and surface processing.

The appearance of timber cladding on a facade is influenced by the number and size of knots, particularly as it weathers over time. Fewer knots create a cleaner, modern look, while more knots contribute to a rustic, textured aesthetic. Small knots offer a refined texture, while large knots add bold character. As the timber ages, knots may darken or lighten differently, creating dynamic patterns. Extractives and resins also impact the appearance and colour changes near the knots. Larger sizes and number of knots increase fibre distortion and therefore reduce the mechanical properties of wood (Zimmer et al., 2020).

Considering the orientation and size of annual rings is crucial in wood processing. Research indicates that boards with narrower growth rings exhibit lower moisture absorption compared to those with wider growth rings. The orientation concerning the wood trunk structure influences how wooden boards shrink. Tangential shrinkage is approximately twice that of radial shrinkage, leading to distortions and increased susceptibility to cracking during the drying process (Fig. 5 and 6). In general, vertical-grain cladding boards demonstrate greater dimensional stability than flat-grain cladding boards.

Cladding elements are produced from timber through either sawing or splitting processes. The latter is primarily used for shingle production, involving the separation of wood along the fibres. This technique results in a surface less prone to water absorption, due to fewer open fibres. On the contrary, sawing entails cutting across the wood fibres, leading to surfaces that readily absorb water because of a higher count of open fibres. To refine the surface texture, timber boards are subjected to planing or sanding. A smoother cladding surface facilitates more efficient water run-off and speeds up the drying process. Furthermore, boards can be grooved to introduce intricacy and texture to the cladding.

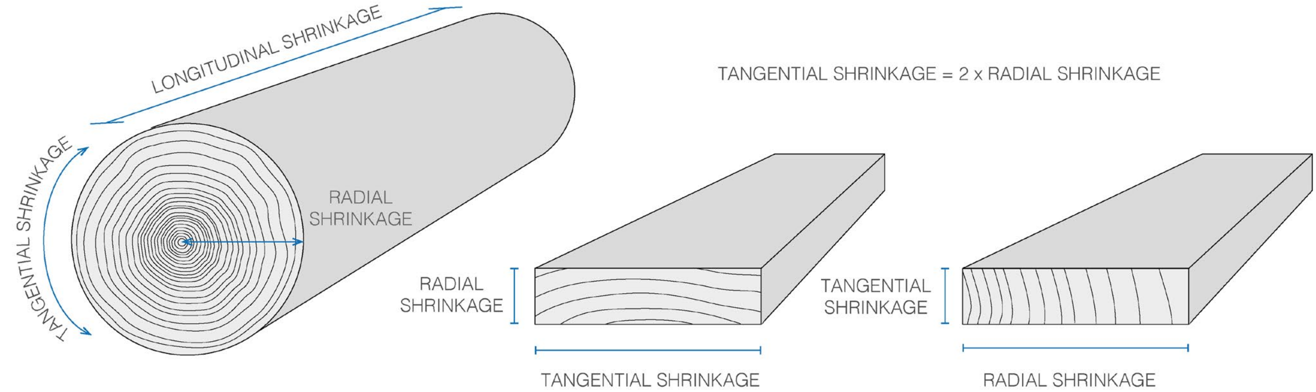


Fig. 6. Dimensional shrinkage of wood. Created by the author.

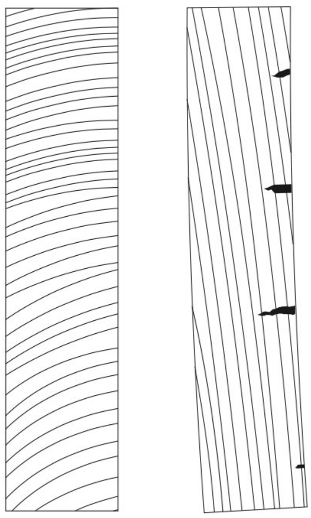


Fig. 7. (left) Vertical grain cladding boards will have greater dimensional stability and be less likely to develop cracks than flat-grain cladding boards. From *Weathering of unpainted wooden façades - Experience and examples* (Zimmer et al., p. 15), by Norwegian University of Science and Technology, 2014.

Fig. 8. (right) Different surface structures in a single plank that has been sawn-cut (on the left) and planed. From *Weathering of unpainted wooden façades - Experience and examples* (Zimmer et al., p. 16), by Norwegian University of Science and Technology, 2014.

2.4. Durability and Use Classes

The durability of a façade depends on material choice, exposure to climate, and design details. Interactions between fasteners and wood matter too. Even with the right wood species, the type and quality of boards impact the wall's appearance. Variations in board quality and texture create visual disparities, while uniformity ensures consistent coloration. Understanding wood durability and use classes is crucial for both structural resilience and visual coherence in wooden structures.

Wood durability, encompassing resistance to decay, damage, and environmental deterioration, is influenced by various factors such as natural resistance, moisture content, insect resistance, treatment methods, exposure to elements, and maintenance practices. The selection of wood for specific applications requires consideration of these factors, as they vary among wood species and conditions, ultimately impacting the performance and longevity of wooden structures and products.

In conjunction with the concept of wood durability, wood use classes play a pivotal role by categorizing wood products based on their exposure to environmental conditions and potential risks of decay or degradation. The European standard EN 335 delineates five use classes shown in Table 2. These use classes guide the selection of appropriate wood species and determine the necessity for protective treatments as shown in Table 3, ensuring that wood products are well-suited to their intended applications. This classification system promotes the longevity and structural integrity of wood by addressing specific environmental challenges each class may encounter.

Table 1. Durability class. According to the European standard EN 350.

Durability class	Description	Wood species (examples)
DC1	very durable	Teak, most tropical species
DC2	durable	Western red cedar, Oak (2-4), Yew
DC3	moderately durable	Larch (3-4), Scots pine (3-4), Douglas fir (3-4)
DC4	sligtly durable	Spruce, Sitka spruce (4-5), Radiata pine (4-5)
DC5	not durable	Aspen, birch, ash, beech, elder, maple, elm; sapwood of all wood species

*The standard applies to solid wood and only heartwood. Sapwood is never durable for any species.

Table 2. Use class. According to the European standard EN 350.

Use classes	General use situation	Moisture content	Critical moisture load
1	interior, dry	Maximum 20% MC	none
2	interior or under cover, water condensation possible	Temporarily >20% MC	every once in a while
3.1	exterior, above ground, exposed to the weather. limited wetting conditions	Temporarily >20% MC	every once in a while
3.2	exterior, above ground, exposed to the weather. prolonged wetting conditions	Frequently >20% MC	frequently
4	exterior in ground contact and/or fresh water	Permanently >20% MC	permanantly
5	permanently or regularly submerged in salt water	Permanently >20% MC	permanantly

Table 3. Durability requirements for wood to be used in different use classes. According to the European standard EN 460.

Use class	Durability class				
	DC1	DC2	DC3	DC4	DC5
1	o	o	o	o	o
2	o	o	o	(o)	(o)
3	o	o	(o)	(o) - (x)	(o) - (x)
4	o	(o)	(x)	x	x
5	o	(x)	(x)	x	x

o – natural durability sufficient; (o) – natural durability is normally sufficient, but for certain end uses treatment may be advisable; (o)-(x) – natural durability may be sufficient, but depending on the wood species, its permeability and end use, wood protection treatment may be necessary; (x) – wood protection treatment is normally advisable, but for certain end uses natural durability may be sufficient; x – wood protection treatment is necessary.

2.5. Untreated Wooden Cladding Variables

The design of wooden cladding presents numerous possibilities, with variations in wood species, tissue, surface quality, and material dimensions. The ways in which cladding can be composed also offer an extensive range of options. At its essence, a fundamental statement outlines the principal elements found in any cladding design: wood undergoes specific processing, is organized into a pattern, and is securely fastened (Hirche, 2014). M. Hirche (2014, p. 37) outlines four main categories of informing the outcome of the cladding design and eventually its weathering tendencies: wood (type), processing, composition and fastening.

The first two categories relate to the 'basic element' of the cladding. Where a basic element is an individual component such as a board, shingle or rafter. The third category is about the arrangement of the basic elements in a certain pattern (composition). Finally, the fourth category is about the finishing touch of the cladding - fastening. Although often overlooked, this final category plays an important role in the appearance and weathering patterns of cladding. Tables 4 - 7 based on M. Hirche's diagrams (2014, p. 40-41) provide an overview of these categories.

The framework offers a comprehensive view of design alternatives, illustrating the numerous variables to consider in the design of wooden claddings. Serving as both a source of inspiration and a decision-making tool in the design process, it facilitates a structured approach to describing and analyzing the components in any cladding. Specifically concerning weathering, the framework provides a methodical approach to identifying elements of interest and relevance to the topic (Hirche, 2014).

Table 4. Category 1

WOOD

Softwood	Hardwood
Western red cedar (Thuja plicata)	European oak (Quercus robur)
European larch (Larix decidua)	Western red oak (Quercus section Lobatae)
Siberian larch (Larix sibirica)	Sweet Chestnut (Castanea sativa)
Douglas fir (Pseudotsuga menziesii)	Eurasian Aspen (Populus tremula)
Scots Pine (Pinus Sylvestris L.)	Poplar (Populus Alba)
European/Norway spruce (Picea abies)	
other	other

*Timber species commonly used for facade cladding. Poplar is added to the chart because it is anomg tree species commonly growing in the Nehterlands and has a potential to be used more with treatment.

Table 5. Category 2

PROCESSING

Wood tissue	Drying	Cutting pattern
sapwood	kiln seasoned	radial sawn
heartwood	air seasoned	tangential sawn
mixed tissue	naturally seasoned	
juvenile wood		
pith		
knotfree		
knot containing		
reaktion wood		
other	other	other

Table 6. Category 3

FASTENING

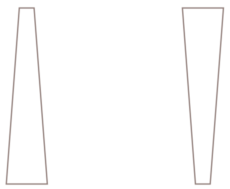
Visible	Invisible
nails	nails
screws	screws
wood nails	wood nails
lashing	lashing
other	other

PROCESSING continued

Shape and dimension	Surface character	Joining
unlimited shapes and dimensions e.g. rectangular square triangular rounded profile board other	sawn planed split ax cut with bark charred surface other	finger- scarf- butt joints other

Table 7. Category 4

COMPOSITION

Position relative to wood stem	Direction relative to cladding	Juxtaposition of basic elements
 pith side bark side  pith side pith side	vertical horizontal other	adjacent non-adjacent (open) overlapping other

2.6. Wood Treatment

The main objective of wood treatment is to enhance timber's durability and performance in a fire. Various methods exist for preserving wood against decay and insect attack. Wood treatment usually is considered to be an environmentally harmful process as most impregnation agents contain toxic active ingredients like copper, chromium or other elements. Nowadays, however, there are a number of environmentally friendly timber treatment options which significantly prolong the lifespan of wood materials.

While this study primarily focuses on the behaviour of untreated wood cladding, it's essential to explore common wood treatment options that have minimal (or no significant) impact on the wood's colour. Timber treated with the methods discussed further undergoes a similar weathering process as untreated wood, making it visually challenging to distinguish between the two. Both Fajer's (2022) and Zimmer et al.'s (2020) research include case studies using specific treatment methods. The following section provides information on environmentally friendly facade cladding treatment options commonly used.

Water-based finishes

Water-based sealers and stains are protective coatings for wood that are primarily composed of water as the solvent or carrier, as opposed to traditional solvent-based counterparts. These sealers and finishes are designed to provide a clear, protective layer on wood surfaces while minimizing the use of volatile organic compounds (VOCs) that can contribute to air pollution. One of the commonly used water-based preservatives is borate-based solution. orates, which are salts derived from boric acid, are known for their low toxicity to humans and animals, making them a more environmentally friendly option compared to certain traditional wood preservatives. All water-based sealers and finishes are often easy to apply, with quick drying times (Water Based Finishes, n.d.).

Linseed oil

Linseed oil, particularly boiled linseed oil, is a traditional wood treatment option that continues to be used in Europe. It is valued for its ability to enhance the natural beauty of wood while providing protection. Linseed oil can be both used clear and tinted if a dark red, brown or yellow colour is desired. Certain treatment methods such as Royal treatment impregnation of wood with linseed oil in a low-pressure plant under vacuum and controlled temperature conditions (Timber Preservation Technologies, n.d.).

Thermally modified wood

Thermally modified wood is widely used in Europe for outdoor applications including facade cladding. The process usually involves heating wood to a high temperature in the range of 160°C to 230°C, in a controlled environment with restricted oxygen levels. Thermal modification improves dimensional stability, and decay resistance and reduces the hygroscopicity of wood (Souza, 2023).

Acetylated wood

Acetylation involves chemically modifying wood to prevent water absorption in its cells, safeguarding the material against rotting, deformation, and insect attacks. The simplified chemical process is depicted in Fig. 10. Accoya wood is a brand of high-performance wood created through a proprietary acetylation process. Due to its widespread availability and unique approach the term “Accoya wood” is often used to refer to “acetylated wood”. The method used by Accoya utilizes softwoods to produce wood endowed with superior durability properties. Uncoated Accoya wood weathers similarly to other wood species, yet this natural weathering process does not compromise the material's durability (Accoya, n.d.).

Fig. 9. Thermally modified wood sample before and after weathering. From *Influence of nanoparticles and olive leaf extract in polyacrylate coating on the weathering performance of thermally modified wood* (Nowrouzi et al., p. 45), European Journal of Wood and Wood Products, 2022.

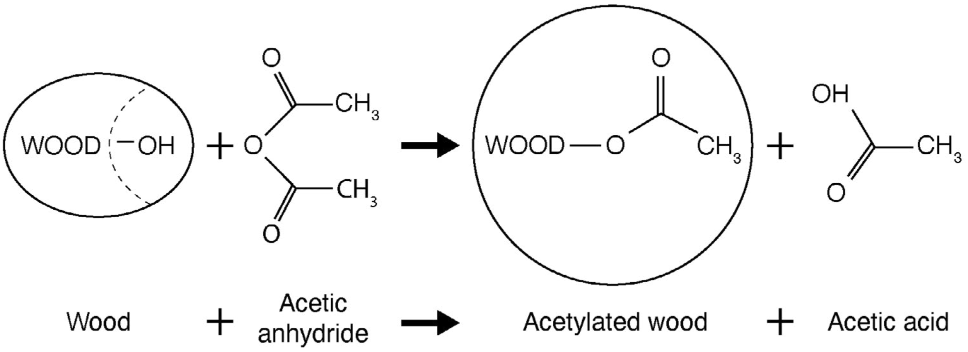


Fig. 10. Chemical process of wood acetylation. Created by the author based on *"Accoya"*, by Accoya, n.d. (https://www.accoya.com/uk/acetylation-what-is-it-and-what-is-acetylated-wood/).

Fig. 11. Weathering of uncoated Accoya wood cladding. Wood City Block project by Anttinen Oiva Architects, Helsinki, Finland. From *"Accoya"*, by Accoya, n.d. (https://www.accoya.com/accoya-weathering/).

3. Wood Weathering & Environmental Agents

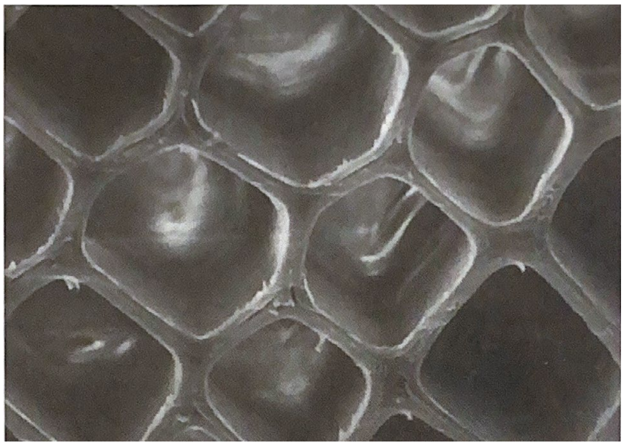
3.1. Weathering Process

Weathering is the broad term which describes the gradual degradation process of materials exposed to the weather. Wood weathering is a process happening only on the surface of the material, and therefore should not be confused with wood decay which affects the whole thickness of bulk (Hirche, 2014, p.11; Roweell, 1984b, p. 141). The surface changes start immediately after the wood is exposed to solar radiation. As Fig. 22. shows, the visual colour changes of wood can be noticed already after a few weeks of exposure, however, according to Rowell (1984b, p.140) it can take more than 100 years to decrease as little as 5-6 mm of the board.

The main causes of wood weathering are solar radiation which causes **lignin degradation** and the wetting and drying process of wood through precipitation resulting in oxidation of extractives travelling towards the surface. Lignin degradation is mostly characterised by darkening of the yellowish-brown wood colour. Other factors include daily and seasonal changes in relative humidity, abrasion by windblown particles, temperature changes, atmospheric pollution, and human activity like mechanical and chemical degradation (Rowell, 1984b, p. 140). Fig. 12. illustrates the effect of wood exposure to 1000h of UV radiation (which is equivalent to a few years of south-facing facade exposure to natural sunlight).

According to Rowell (1984b) wood weathering primarily refers to the lignin degradation processes mentioned above. Some researchers, however, describe other related processes causing visible changes in the wood surface. Zimmer et al. (2020) identify five main factors contributing to surface deterioration: lignin degradation, blue-stained fungi, facade leaching, mechanical erosion, and biological surface growth.

Blue-stained fungus is a common name for mould (the most common microorganism found on weathered wood) which causes dark blue and black colour changes on the wood cladding. The growth of blue-stained fungi is accelerated by the long exposure of wood to moisture and high air humidity. The facades covered in blue-stained fungi appear especially dark when wet, when they dry out the colour appears notably lighter (Zimmer et al., 2020). Blue-stained fungi cause little material strength loss and cause more visual changes than actual degradation of wood (Rowell, 1984b).



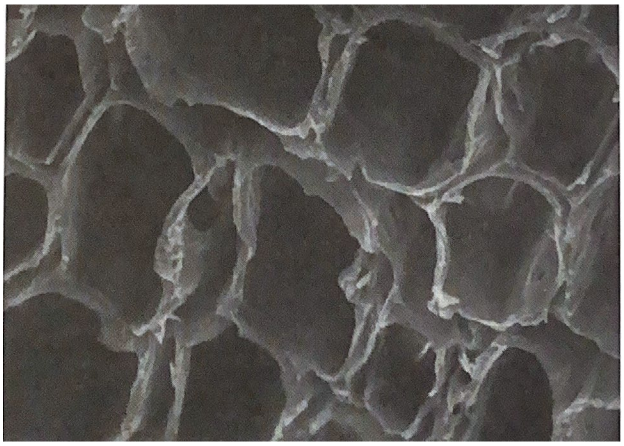


Fig. 12. (left) Southern pine cross-section (1000x). (right) Southern pine cross-section following 1000h of UV radiation (λ>220 nm, 1000x). From *"Handbook of Wood Chemistry and Wood Composites"*, by CRC Press, 2005.

Leaching refers to the process by which certain substances, such as water-soluble chemicals or compounds, are gradually removed or washed out from the surface of wooden elemetns. Wood leaching occurs due to exposure to environmental factors like rain, snow, or humidity, causing water to carry away soluble components from the wood. This process can lead to changes in the appearance and properties of the wood, exposing the cellulose in the wood fibres and turning the facade colour grey or silver (Zimmer et al., 2020).

Mechanical erosion refers to the abrasion of windblown particulates like ice and sand. Little particles carried by the wind can "sand" the surface of the wood causing surface erosion as well as preventing the growth of fungi or biological agents (Zimmer et al, 2020). Wind also contributes to faster drying of the cladding, therefore wood facades in windy areas usually have little growth of mould, algae, moss and lichens.

Biological surface growth includes different biological agents colonising wood surfaces. Moss, lichens and algae commonly prefer environments with high relative humidity, low temperature, low airflow environments and low exposure to sunlight. They also indicate favourable conditions for wood-decay fungi growth. Additionally, biological growth contributes to capturing and preserving the moisture on the cladding surface (Zimmer et al, 2020).

Fig. 13. (left) Blue-stained fungi growth. From "*ArchDaily*", by Carl-Viggo Hølmebakk, 2022. (https://www.archdaily.com/801224/summer-house-gravrak-carl-viggo-holmebakk?ad_medium=gallery).

Fig. 14. (right) Facade leaching. From "*East Brothers Timber*", n.d. (https://eastbros.co.uk/products/cladding/feather-edge).

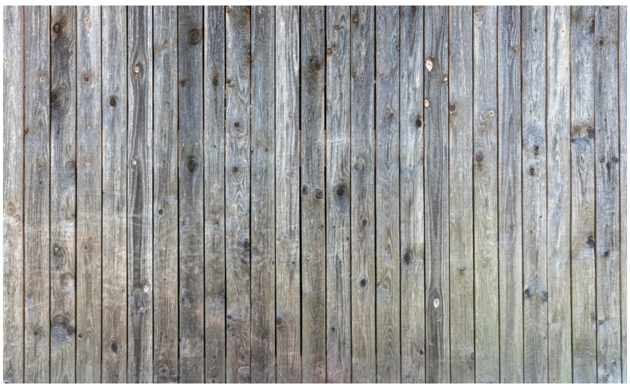


Fig. 15. (left) An old façade characterized by mechanical erosion. Vigdalen, Luster. From *Weathering of unpainted wooden façades - Experience and examples* (Zimmer et al., p. 23), by NIBIO/Lone Ross Gobakken, 2014.

Fig. 16. (right) Biological growth on facade surface. From "*Adobe Stock*", by Peter Togel, n.d. (https://stock.adobe.com/nl/images/grey-barn-wooden-wall-planking-texture-hardwood-dark-weathered-timber-surface-old-solid-wood-slats-rustic-shabby-gray-background-grunge-faded-wood-board-panel-structure-close-up/517528282).

3.2. Climate Studies

A combination of climate and local environmental factors influences the weathering of untreated timber cladding. Due to the approach of this study of translating the existing research on timber cladding weathering to the context of the North Netherlands, the collection and representation of weather data is an essential part of the research. The primary weather factors responsible for wood weathering are wind-driven rain (WDR) and solar radiation, specifically ultraviolet (UV) radiation (Hirche, 2014). In the following section, the climate studies are documented in the form of weather maps and diagrams.

Radiation is one of the foremost degrading agents in the weathering processes (Rüther, 2011). The solar radiation intensity is measured in Watts per square meter (Wh/m^2). It can be represented in graphs or maps as well as using digital 3D simulation tools (sometimes referred to as surface weather maps). In the context of weather maps, a relevant metric depicting exposure to solar radiation is sun hour data, denoted in hours per year (h/y). When both solar radiation and sun hour data are presented using polar diagrams, they convey analogous visual information, rendering them potentially interchangeable as tools for documenting sunlight exposure.

Fig. 19. depicts the approximate amount of solar radiation on vertical surfaces (kWh/m^2). The solar radiation diagram was produced employing the data from Beale's (2022) Peak Sun Hours Calculator which allows the prediction of the annual amount of solar radiation taking into consideration the surface's angle of inclination relative to the ground surface and orientation relative to the cardinal direction in a specific location.

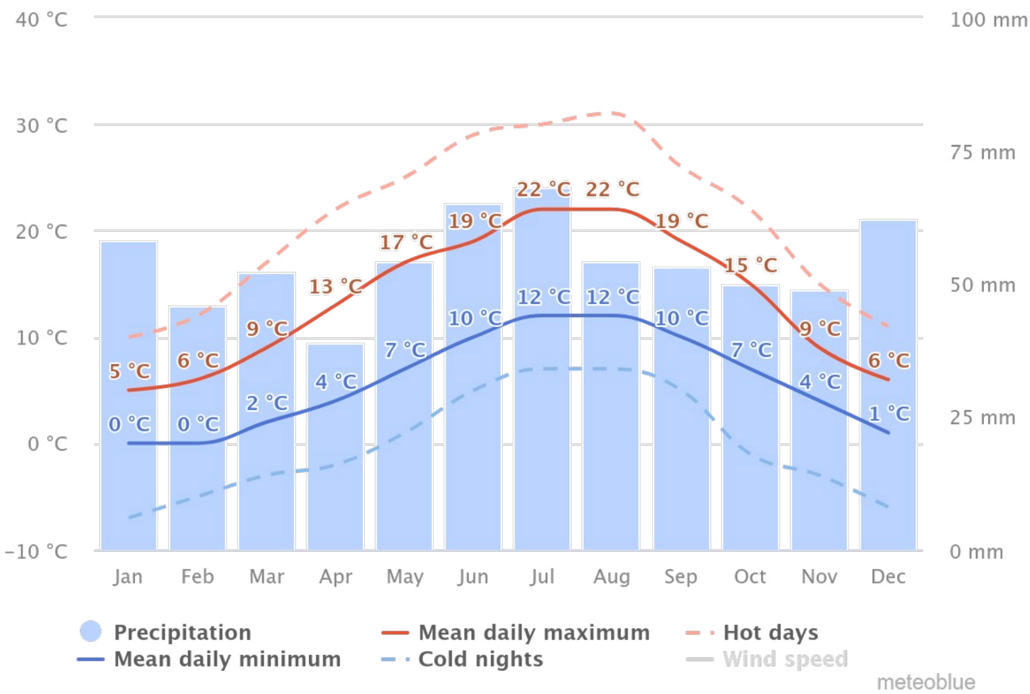


Fig. 17. Average temperatures [°C] and precipitation [mm/month] in Groningen. From "Meteoblue" n.d. (https://www.meteoblue.com/en/weather/historyclimate/climatemodelled/groningen_netherlands_2755251).

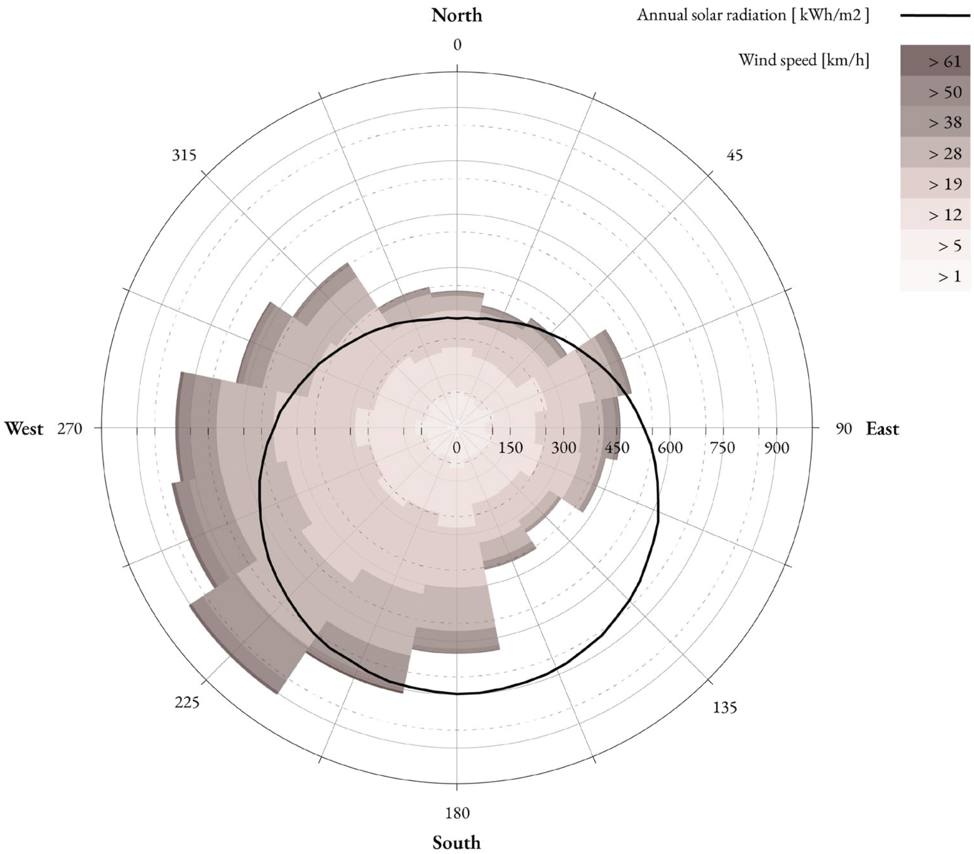


Fig. 18. Wind rose [h/y] showing the distribution of wind direction and wind speed [km/h] and annual solar radiation [kWh/m2] for vertical surfaces for Groningen. Created by the author.

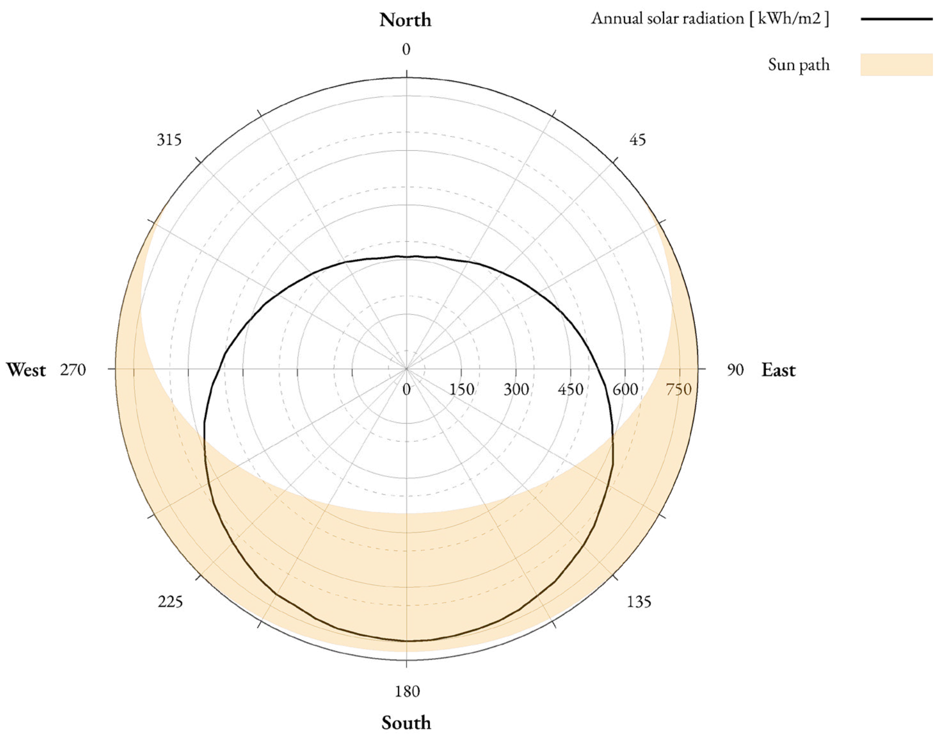


Fig. 19. Annual solar radiation [kWh/m2] for vertical surfaces and sun path for Groningen. Created by the author.

Along with the diagrams illustrating wind-driven rain (WDR) and solar radiation, this chapter incorporates graphs presenting annual precipitation levels and temperature variations. Furthermore, a wind rose diagram is featured. Wind direction data typically represented as a wind rose, is generally more accessible compared to WDR data. While wind roses do not provide information on precipitation, they can function as an alternative indicator for estimating WDR direction when obtaining WDR data is not feasible.

Wind-driven rain (WDR), another significant factor in timber weathering, is measured in millimetres per year or recorded as wind-driven rain events with wind speed measurements in meters per second (m/s). Hirche (2014) and Rüther (2011) employed the use of polar diagrams, which incorporate data on exposure to solar radiation and WDR. These diagrams, known as directional weather maps, offer advantages over the more commonly used bar charts. They enable a smoother transition of information for both on-site observations and the development of situational plans.

To establish a foundation for comprehending the local climate's influence on the weathering process, weather maps that provide data on solar radiation/ sun hours and WDR were created (Fig. 20). The WDR maps were created based on the open data from KNMI - Royal Netherlands Meteorological Institute (n.d.) on the direction of the wind and amount of precipitation for each year of the day in Louwersoog. The final weather map shows the average WDR for the past 10 years.

Employing consistent weather maps allowed for further translation of existing research findings into the unique climate conditions of this region. Fig. 21. shows the differences in the amount and direction of WDR in Lauwersoog compared to Trondheim, where a significant amount of existing research has been done. This step was essential to gain a deeper understanding of how the North Netherlands' climate affects the weathering of untreated timber facades. The findings are documented in the "Weathering and Design" section pp. 28-45.

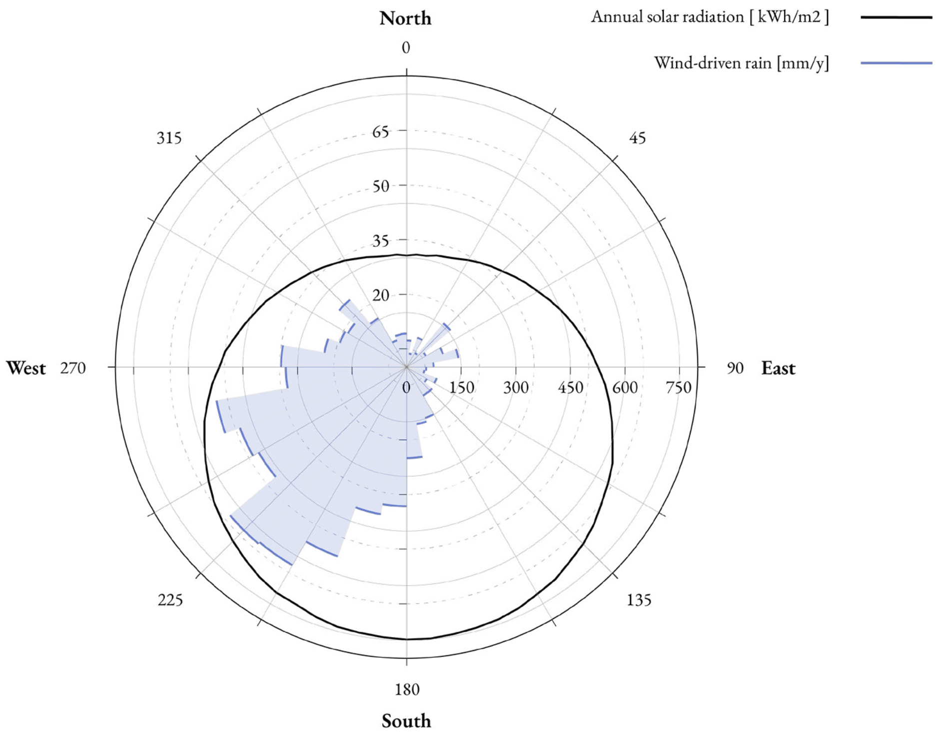


Fig. 20. Wind-driven rain [mm/y] distribution and annual solar radiation [kWh/m²] for vertical surfaces in Lauwersoog. Created by the author.

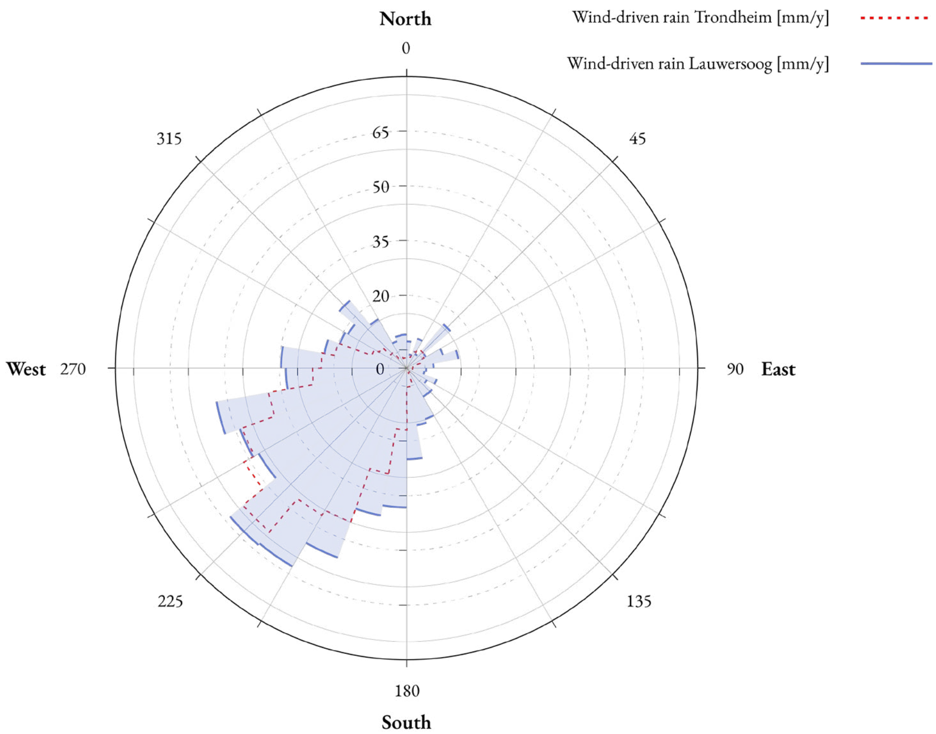


Fig. 21. Wind-driven rain [mm/y] in Lauwersoog compared to wind-driven rain data in Tronheim. Created by the author.

4. Design & Weathering

4.1. Position Relative to the Cardinal Direction

The correlation between the facade's cardinal direction and the weathering process is intricately tied to local climate conditions. The general prognostications concerning colour development, dependent upon varying orientations of the facade samples, are based on the experimental investigations conducted by M. Hirche (2014) and Rüther (2011) in Trondheim, Norway. To contextualize these findings within the North Netherlands region, a comparative analysis is undertaken by aligning the weather maps utilized in Hirche's study with those expounded in section 3.2. Climate Studies, specifically addressing weather conditions in the North Netherlands.

The following predictions delve into the impact of two environmental factors: exposure to wind-driven rain (WDR) and exposure to solar radiation, primarily ultraviolet (UV) radiation. Noteworthy is the influence of the latter on the Time of Wetness (TOW) factor. Reduced exposure to solar radiation slows down the drying process, establishing conditions favourable to fungal growth for longer periods in comparison to sun-exposed surfaces.

It is important to note, that the WDR direction and index of solar radiation in the North Netherlands are vastly similar to those in Trondheim with a slightly higher average precipitation level in the Netherlands. Therefore, the majority of experiments conducted in Trondheim can be used to represent the weathering predictions for this study.

PREDICTIONS ON COLOUR DEVELOPMENT IN THE PROCESS OF WEATHERING:

WEST

The west-facing facade is expected to develop the darkest grey colour. This is explained by the exposure to excessive amounts of WDR in combination with high exposure to solar radiation.

SOUTH

The south-facing facade is expected to develop the second-darkest grey colour. The weather map suggests that the south facade would be exposed to similar amounts of WDR as the west facade. The high amount of solar radiation, however, along with degrading the surface structure of wood, contributes to faster drying of wood therefore slightly slowing down the development of a dark grey colour.

NORTH

According to Hirche's research, the north-facing facade is expected to develop a slightly lighter grey colour than the south-facing facade. Even though the exposure to WDR is very low, the north-facade, darkening of wood is explained by the high time of wetness. It is important to note that the amount of WDR coming from the north is higher in Lauwersoog than in Trondheim, which only contributes to the development of dark grey colour.

EAST

The east-facing facade is characterised by the slowest development of the grey colour. Relatively high exposure to sun radiation and very low exposure to WDR keeps the moisture content very low. Unlike others, the east-facing facade is expected to develop a darker brown colour.

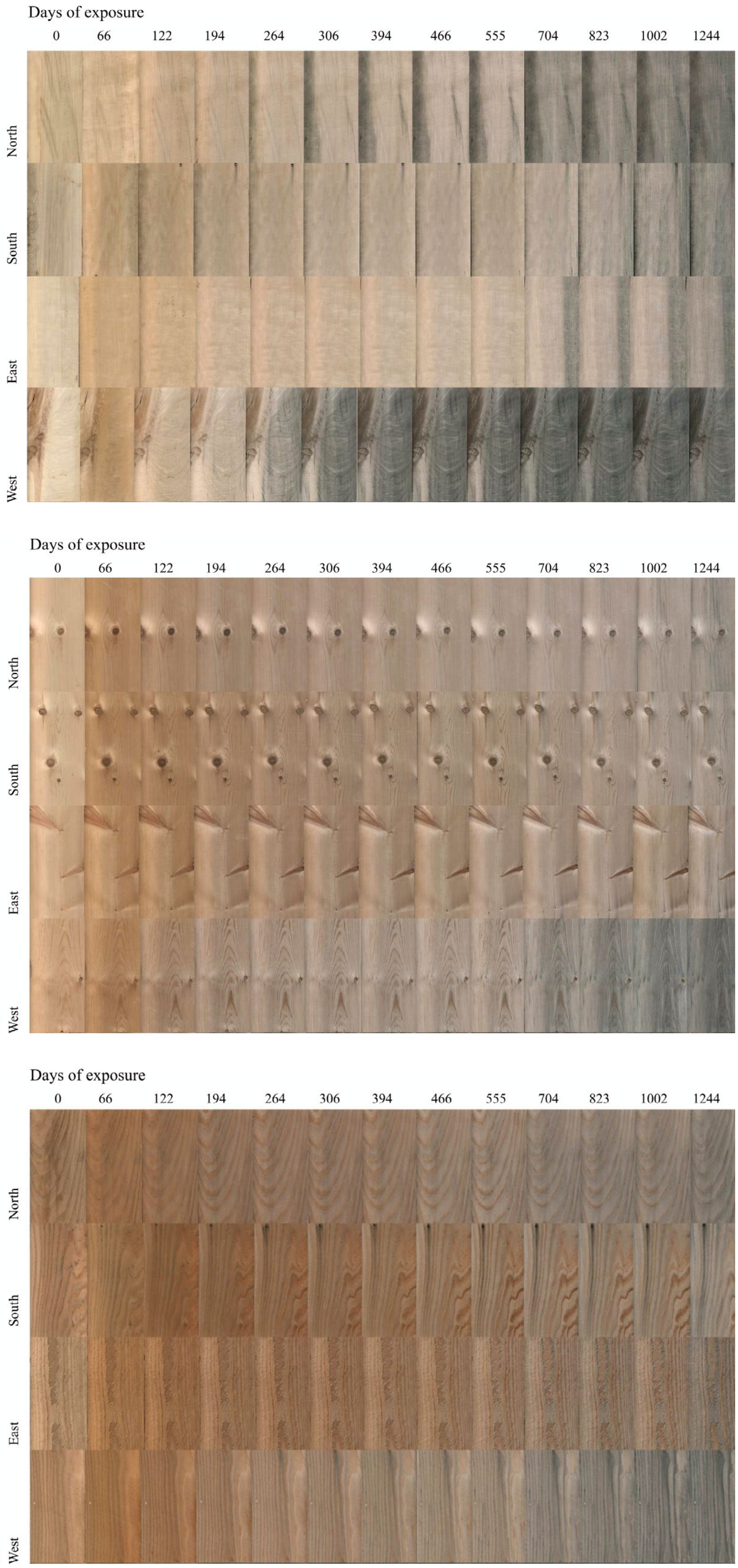


Fig. 22. Aspen (top), Scots Pine (middle), Larch (bottom) heartwood sample scanned images from the outdoor weathering experiment. The number on top indicates exposure time in days. From *Wood Weathering from a Service Life Perspective* (Rüther, pp. 125-127), Norwegian University of Science and Technology, 2011.

4.2. Cladding Design

Cladding design is a complex aspect, involving a diverse array of cladding types. As indicated in Table 7 (p.17), variations in cladding designs are influenced by factors such as the placement relative to the wood stem, orientation in relation to the facade surface, and the arrangement of basic cladding elements. Despite the existence of several common timber cladding types, one has the flexibility to modify and combine them, resulting in an extensive range of design possibilities. While Hirche's study primarily delves into the correlation between cladding type and weathering, this section offers a broader perspective on the characteristics of wood weathering based on general cladding design options.

The selection of cladding type significantly influences the aesthetic aspects of a weathered facade. The research shows that the composition of the facade elements has a more significant role in the weathering process than inferent wood species (Zimmer et al., 2020). The following section presents predictions and remarks on the colour and pattern development during free-standing vertical facade panel weathering. Four commonly used types of cladding were selected for discussion: two cladding types with non-overlapping boards and two cladding types with overlapping elements.

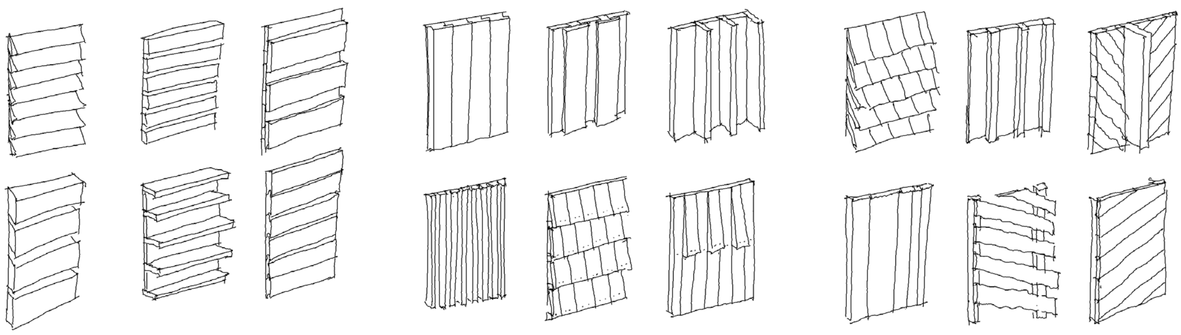


Fig. 24. Timber cladding variations. Sketch by the author.

Fig. 23. Photo showing the south facing structural frame at Voll, Trondheim used for Hirche's experimental reserch. From *Wood Weathering as Design Option* (Hirche, p. 76), by M. Hirche, 2014, Norwegian University of Science and Technology. Copyright [2014 by Majbrid Hirche.

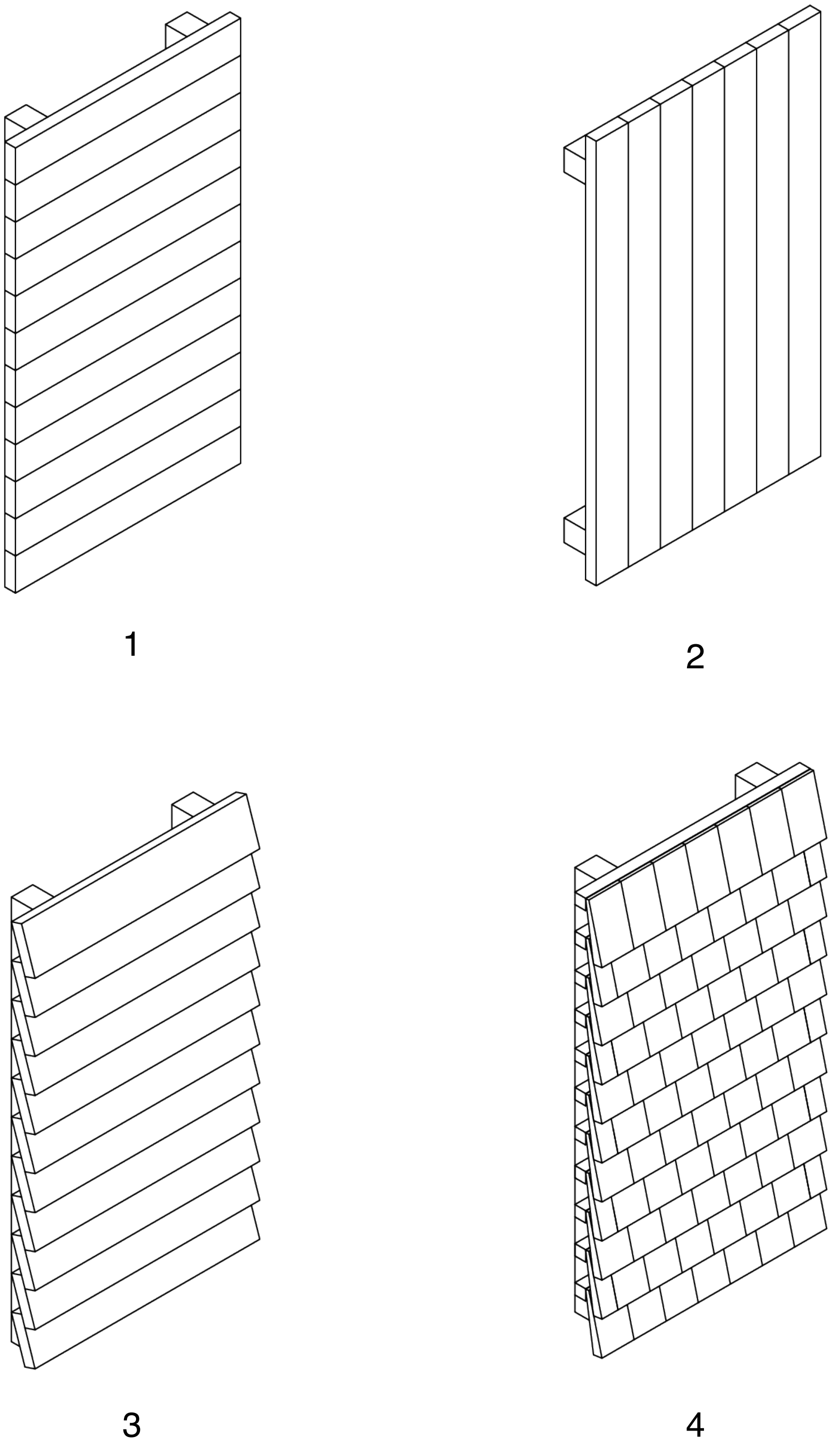


Fig. 25. Cladding types: 1. Horizontal cladding; 2. Vertical cladding; 3. Cladding with overlapping boards; 4. Schingle cladding. Created by the author.

4.2.1. Claddings with Non-overlapping Elements

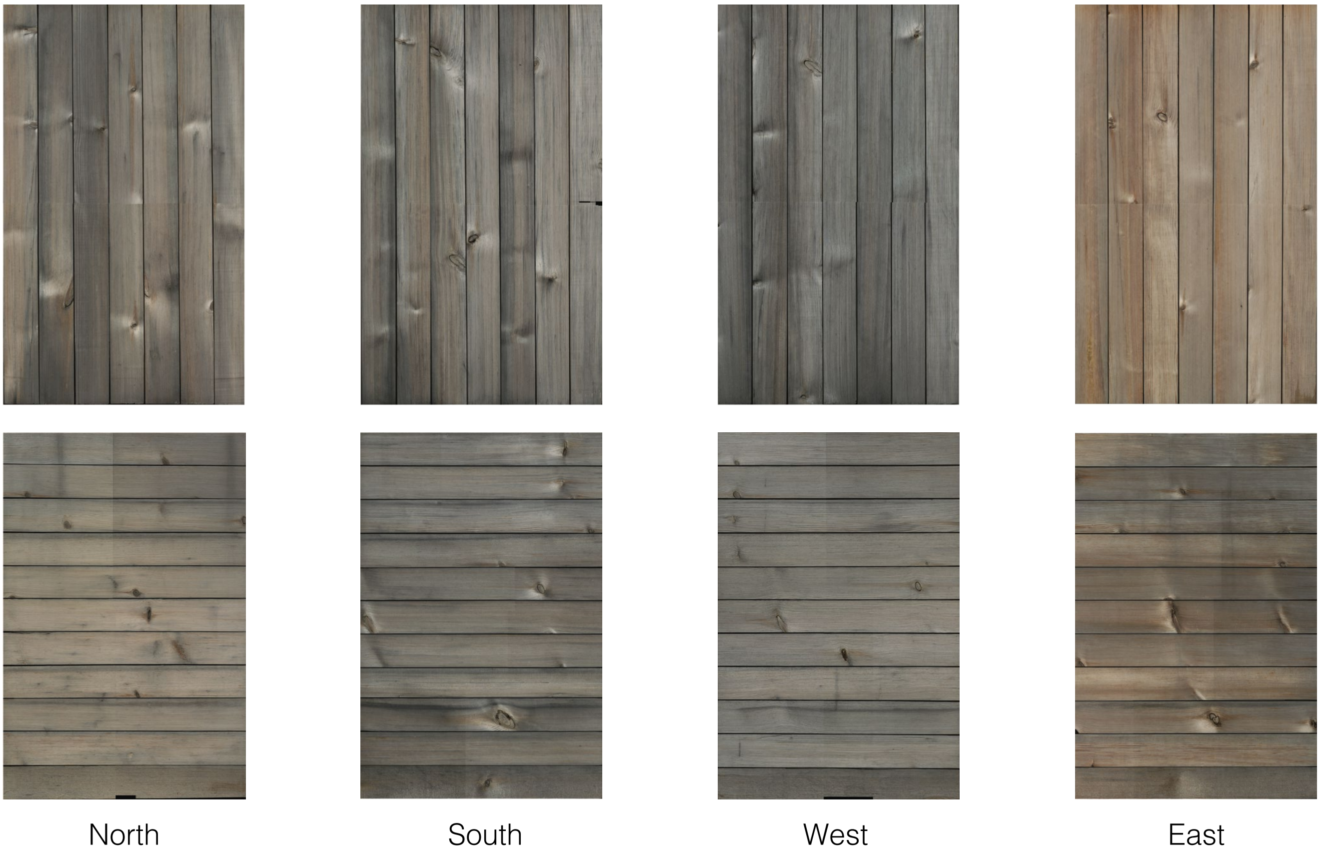
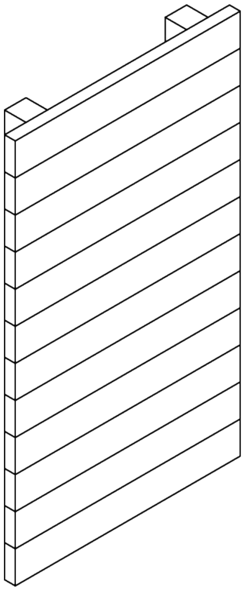
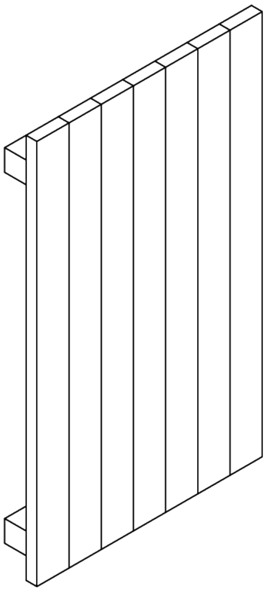


Fig. 26. Free-standing cladding samples exposed to wethering for 20 months in Trondheim. From *Wood Weathering as Design Option* (Hirche, pp. 100 - 103; 140-143), by Norwegian University of Science and Technology, 2014.

Fig. 27. (left) Siberian Larch cladding sample. From “*Russwood”,* by Russwood, n.d., (https://www.russwood.co.uk/cladding/products/sila-select-siberian-larch/).

Fig. 28. (right) Vertical cladding. From *“Pinterest”*, by Hedvig Skjerdingstad / MiMa Studio, n.d. (https://www.pinterest.co.uk/pin/582794008057794618/).



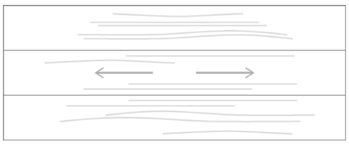


HORIZONTAL CLADDING

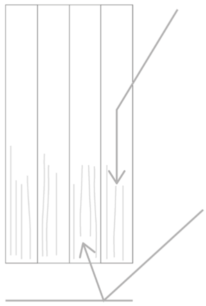
Horizontal cladding is one of the most commonly used timber cladding types. The plane horizontal and vertical board claddings have a non-shaded type of geometry which allows for uniform weather exposure over the total surface area. In horizontal cladding types, water runs sideways along the cladding grain as well as downwards, creating watercolour-like patterns on the facade (Zimmer, et al., 2022, p. 49). Cladding types 1 and 2 set general rules on colour development according to the cardinal direction regardless of the position of the boards (Hirche, 2014).

VERTICAL CLADDING

Vertical claddings are considered to be more problematic in wet environments. The section nearest to the ground typically experiences the highest levels of moisture exposure, being wetted by both rainwater flowing down the boards and splashing from the ground. To mitigate end-grain water absorption, the lower edges of the boards are often chamfered. In cases of wood-decay fungi affecting the lower portion of vertical cladding, the replacement of all affected boards becomes necessary. Horizontal claddings offer an advantage in this regard, as only the lower boards need replacement in the event of decay damage near the ground. (Zimmer et al., 2020, p. 28).



WATER MOVEMENT ALONG THE FIBRES



4.2.2. Claddings with Overlapping Elements

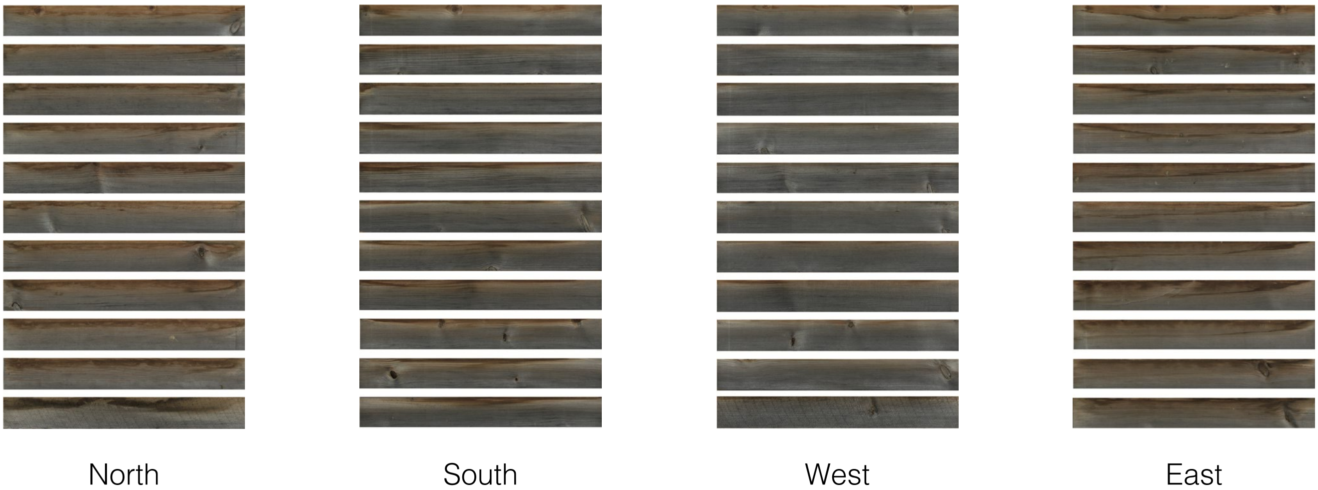
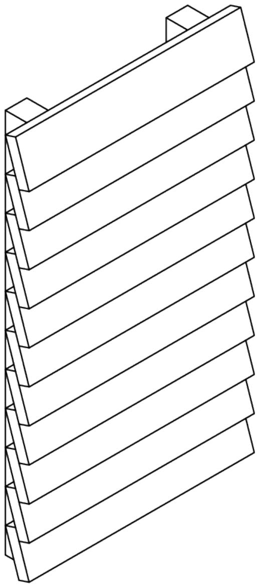


Fig. 29. Free-standing cladding samples exposed to wethering for 20 months in Trondheim. From *Wood Weathering as Design Option* (Hirche, pp. 180-187), by Norwegian University of Science and Technology, 2014.

Fig. 30. (left) Horizontal cladding of overlapping boards as used in Western Norway. From *Weathering of unpainted wooden façades - Experience and examples* (Zimmer et al., p. 28), by Norwegian University of Science and Technology, 2014.

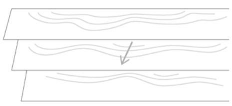
Fig. 31. (right) Overlapping shingle cladding, Vikki Church, Helsinki, Finland. From *"Behance"*, by Daniel Annenkov, 2019 (https://www.behance.net/gallery/82952351/Vikki-Church-JKMM-Architects).



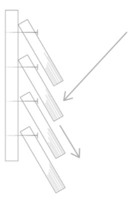
CLADDING WITH OVERLAPPING BOARDS

Generally, horizontal claddings with overlapping elements are commonly used in regions with a lot of rain as they provide good protection against wind-driven rain. A horizontal cladding of overlapping boards can vary widely in colour. Lower parts of the board can develop a clearer grey colour because they are subjected to the rain. The upper parts are protected by the overhanging board and can appear more brown (Zimmer et al., 2020, p. 28).

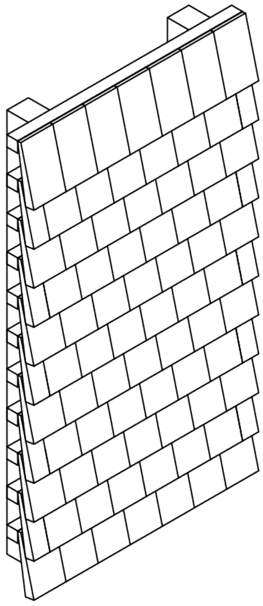
In the cladding with overlapping boards as well as shingle cladding, one can sometimes notice characteristic brown or dark brown extractive stains around the junction of two cladding elements (Fig. 7 - 8). The colour difference appears due to the fact, that the upper part of the boards is shaded by an overhanging top board therefore the lower exposure to WDR and solar radiation and different times of wetness.



LEACHING

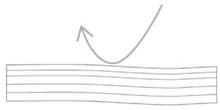


WATER RUN-OFF

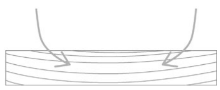


SHINGLE CLADDING

Historically wood shingles have been used as roof cladding, for example on medieval churches in north-western Europe. In contemporary times, there is a growing trend of utilizing shingles for facade cladding. Traditionally, cladding shingles have been meticulously crafted by hand, involving the careful splitting of knot-free wood pieces with minimal fibre distortion. The inherent benefit of split wood shingles lies in their surface alignment with the natural grain of the wood. This characteristic results in fewer exposed fibres, rendering the surface more moisture-resistant than cut or sawn surfaces (Zimmer et al., 2020, p. 29).



SHINGLES MADE BY SPLITTING ALONG THE ANNUAL RINGS REPEL MOISTURE



SAWN BOARDS ABSORB MOISTURE

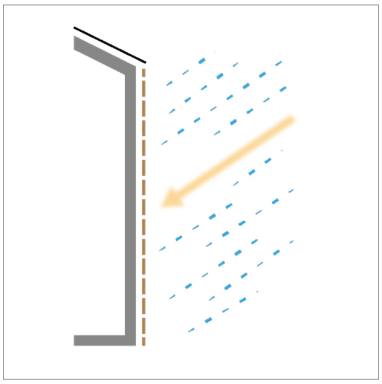
Fig. 32. (left) Overlapping shingle cladding, Vikki Church, Helsinki, Finland. From *"Behance"*, by Daniel Annenkov, 2019 (https://www.behance.net/gallery/82952351/Vikki-Church-JKMM-Architects).

Fig. 33. (right) Wood shingle cladding of Scots pine heartwood. Technical workshop, Rena Military Camp. From *Weathering of unpainted wooden façades - Experience and examples* (Zimmer et al., p. 29), by Norwegian University of Science and Technology, 2014.

Fig. 34. (left) Wideboard vertical timber cladding of a shed in Reitdiep area, Netherlands. Photograph made by the author.

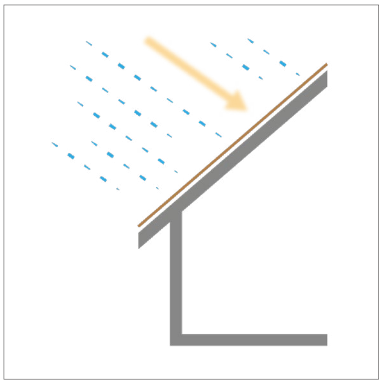
Fig. 35. (right) Vertical freshly sawn timber rainscreen weathering detail, the UK. From “English Woodlands Timber”, n.d. (https://www.englishwoodlandstimber.co.uk/product-type/fresh-sawn-timber-cladding/).

4.3. Architectural Design and Detailing

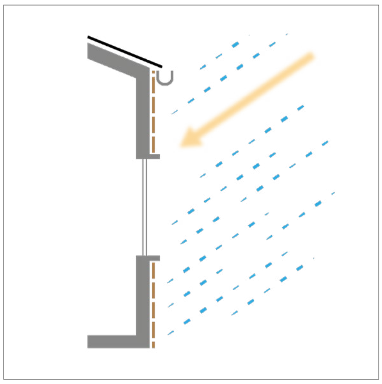


Vertical surfaces

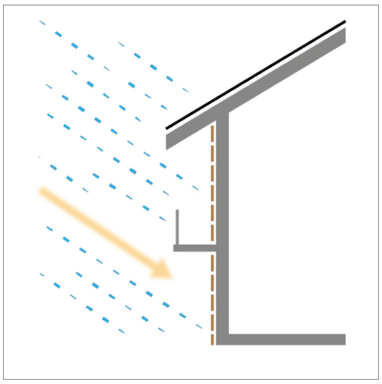
Tilted surfaces



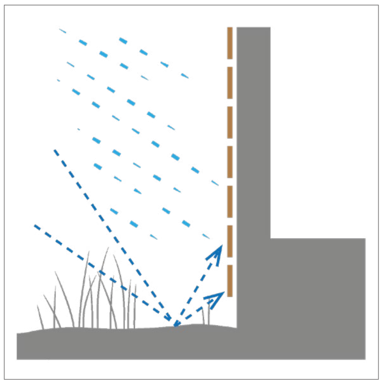
Roof cladding



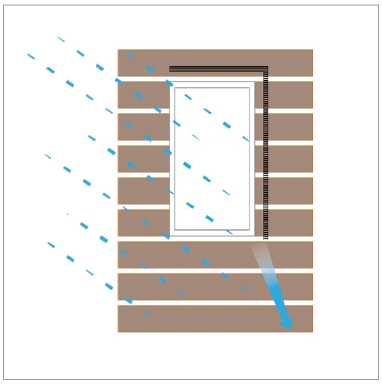
Moulding and windows



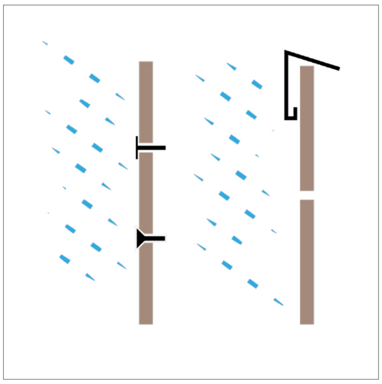
Cantilevered componenets



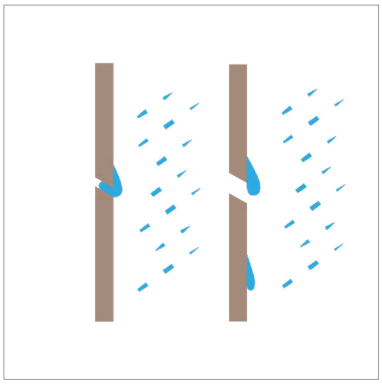
Ground-level cladding



Water run-off



Fixings, fasteners and hardware



Joints

Fig. 36. Architectural and detail design diagrams. Created by the author based on *Weathering of unpainted wooden façades - Experience and examples* (Zimmer et al., pp. 30-56), by Norwegian University of Science and Technology, 2014.

Typically, a building's facade constitutes an intricate system including windows, doors, joints, a drainage system, and various other projecting or offset elements. Diverse architectural details play a crucial role in shaping the microclimate of the facade, leading to uneven weathering across the entire facade surface. This chapter provides an overview of how different architectural designs influence the weathering of wooden-clad facades, drawing heavily from Zimmer et al.'s report on the Weathering of Unpainted Facades (2020, pp. 30-56).

Vertical surfaces

A plain wall with minimal details tends to change colour evenly in similar weather conditions. To maintain a good appearance, it's important to ensure proper ventilation behind the wall. This is usually achieved by using battens, allowing air to circulate behind the boards. However, making the gaps between the boards too narrow might affect ventilation and slow down the drying process (Zimmer et al., 2020).

Tilted surfaces

For walls with a slope, the angle determines how they face different weather conditions. When the lower part tilts inward, the wall gets less wet, stays shaded, and retains its original colour for a longer time. However, local factors can sometimes lead to high humidity and the growth of blue-stain fungi. On the other hand, walls with the lower part tilted outward, like those in roofs or upper parts of complex structures, are more exposed to weather conditions.

The slope of a tilted wall also affects how rainwater runs off and changes the wall's colour. Walls tilting outward might get wetter and change colour faster than vertical walls. Additionally, the slower runoff on tilted surfaces can hinder the drying process, encouraging the growth of fungi, algae, moss, and lichens. (Zimmer et al., 2020).

Roof cladding

Timber cladding is not commonly used for flat roof cladding due to several reasons related to its structural and performance limitations. Flat roofs are more prone to water accumulation and moisture retention, posing a significant risk to timber as it can easily absorb water, leading to decay, warping, and rot. Additionally, maintaining a consistent protective finish on timber cladding in flat roof applications can be challenging, as exposure to harsh weather conditions can accelerate deterioration.

Timber boards, however, are commonly used for rooftop decks and terraces. In such applications, proper waterproofing and drainage systems are crucial to prevent water damage to the timber. The gap between the waterproofing layer and the timber boards allows for sufficient ventilation. Horizontally placed boards are subject to high solar radiation exposure and high water loads, therefore change their natural colour fast after installation if not treated.

Pitched roofs clad with timber have the same weathering process as facades with the lower part tilted outwards described in the section above.

Joints

The way joints are shaped affects the colours on the facade. The wood is sensitive to getting wet at the joints, especially where the end part is exposed. Water is absorbed through small openings in the wood. So, it's important to design joints and details to prevent too much water from getting in and help the wood dry properly. If it stays wet for a long time, it can cause colour differences on the facade and allow wood-decay fungi to grow (Zimmer et al., 2020).

Moulding and windows

Any interruption in a facade, such as windows and mouldings, influences how the sun and rain affect the cladding, potentially causing noticeable colour differences. Even small projections can lead to variations in colour. Both vertical and horizontal trim boards may contribute to differences in cladding colour. Installing metal flashing is essential for fire protection.

Varying thicknesses of cladding boards can result in variations in the facade's depth and help blend the transitions between differently coloured segments (Zimmer et al., 2020).

Cantilever components

Balconies, roof overhangs and other cantilevered building components create more varied microclimates than moulding elements. These elements can result in significant colour differences. The way colours vary depends on how the facade faces, the direction of rain, and the angle. Most of the colour differences come from the protection these protruding elements offer against the sun and rain.
In certain cases, areas shielded from rain, like under eaves and overhangs, can collect moisture without much washing away. This can produce unique, wavy, watercolour-like colour effects (Zimmer et al., 2020).

Ground-level cladding

The shape and design of ground-level cladding significantly impact a building's appearance, especially the exposed end grain in vertical claddings and the lower boards in horizontal ones close to the ground, which face splashes of rainwater. The distance between the cladding and the ground is crucial in determining the moisture load on the cladding. The type of pavement or ground surface also affects this load; gravel and grass typically result in less splashing and soiling, while hard or non-porous ground covers can increase moisture. Maintaining a good distance between the cladding and the ground is recommended. Accessibility requirements and a desire for seamless adaptation to the terrain have led to detailed solutions using gutters, surfaces, and materials, allowing for a closer cut to the ground.

Without special protective measures, it's advisable to keep at least a 30 cm distance between the bottom of the cladding and the ground to minimize colour changes in the lower cladding boards. Protruding elements on the facade or concrete foundations can cause back-spray and capillary sorption through the end grain of cladding boards. Roof overhangs act as protection against high water loads and reduce splashing from the ground. Different ground covers result in varying amounts of back-spray and soiling on the lower part of the cladding (Zimmer et al., 2020).

Water run-off

Water running off from building elements like window trims, sunscreen lamellas, and balconies plays a role in the facade's colour variations. The positioning of boards on the facade greatly influences how water flows. On vertically clad facades, areas of different colours often exhibit distinct borders due to the orientation of the boards. In horizontal claddings, water doesn't just run straight down but also sideways, influenced by the cladding profile and the fibre orientation in the boards, creating watercolour-like colour patches. Extensive water runoff can lead to leaching marks on the facade (Zimmer et al., 2020).

Fixings, fasteners and hardware

Wooden claddings frequently interact with metals used in fixtures, gutters, downpipes, flashings, hardware, and trims across roofs, facades, and windows. Certain combinations of wooden cladding and metal can lead to color changes in the wood. Factors contributing to this include corrosion, chemical reactions between the metal and wood, as well as leaching and runoff from the metals. Metal runoff can also hinder the growth of blue-stain fungi.

During the installation process, hot-galvanized or galvanized nail and screw heads may sustain damage as they penetrate the wood. These fine cracks in the anti-corrosion layer can result in rust formation and the runoff of rusty water, leaving grey and black stripes on the facade. (Zimmer et al., 2020)

Fig. 37. (left) Window of Peter Zumthor's office. From "*Flickr*", by Nicole Alvarez, 2011. (https://www.flickr.com/photos/himynameisnicole/5345924569/in/photostream/).

Fig. 38. (right) Weathered cladding detail, project by Ruinelli Architetti. From "*Divisare*", by Tina Mott, n.d. (https://divisare.com/projects/471008-ruinelli-architetti-vaclav-sedy-falegnameria).

Fig. 39. (left) Tou Park facade with balconies, project by Alliance Architects, Norway. From "*Alliance Architecture Studio*", 2013. (https://www.allark.no/projects/tou-park-stavanger).

Fig. 40. (right) Tilted and vertical surface weathering, Rythm House by Julius Taminiau Architects, the Netherlands. From "*ArchDaily*", by Norbert Wunderling, 2020. (https://www.archdaily.com/949982/rhythm-house-julius-taminiau-architects).

Fig. 41. (left) Falegnameria by Ruinelli Architetti, Switzerland. From "*Divisare*", by Tina Mott, n.d. (https://divisare.com/projects/471008-ruinelli-architetti-vaclav-sedy-falegnameria).

Fig. 42. (right) Facade and door detail of Atelier Peter Zumthor & Partner AG. From "*Atlas of Places*", Hélène Binet, Hans Danuser 2019. (https://www.atlasofplaces.com/architecture/zumthor-studio/).

Fig. 43. (left) Chesa Futura by Foster & Partners, Switzerland. From "*Arquitectura Viva*", by Nigel Young, n.d. (https://arquitecturaviva.com/works/chesa-futura-4).

Fig. 44. (right) House of offcuts by Kolman Boye, Norway. From "*Dezeen*", by Johan Dehlin, 2023. (https://www.dezeen.com/2023/02/27/saltviga-house-kolman-boye-architects-dinesen/#/).

Fig. 45. (left) Summer House Gravråk by Carl-Viggo Hølmebakk, Norway. From "*ArchDaily*", by Carl-Viggo Hølmebakk, 2022. (https://www.archdaily.com/801224/summer-house-gravrak-carl-viggo-holmebakk?ad_medium=gallery).

Fig. 46. (right) House at the Stürcherwald. From "Bernardo Bader Architecten", by Bernardo Bader Architects, 2016. (https://www.bernardobader.com/en/projekt/haus-am-stuercher-wald).

5. Conclusion

5.1. Design Strategies

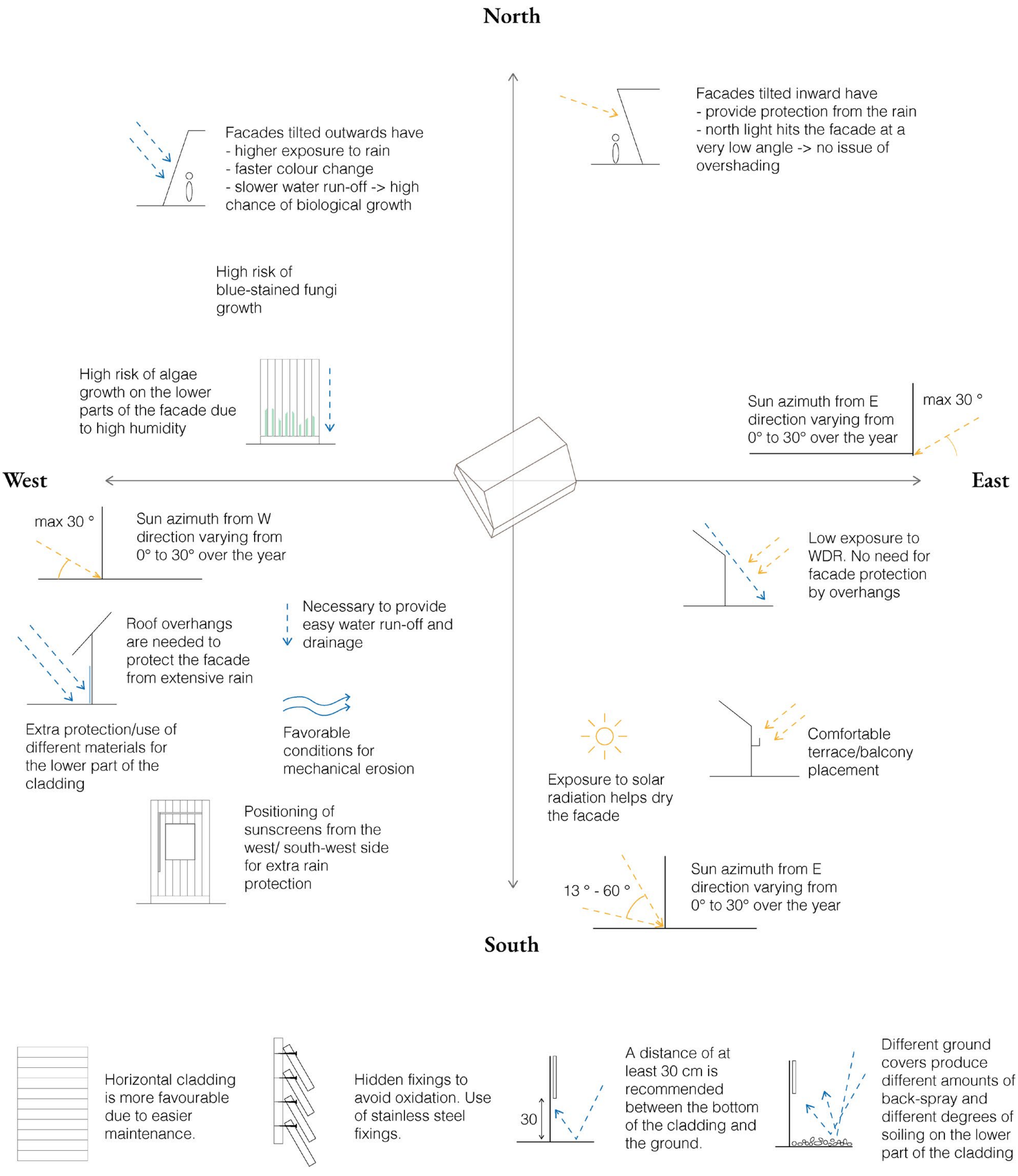


Fig. 47. Designing with Weather: Design Strategies. Created by the author.

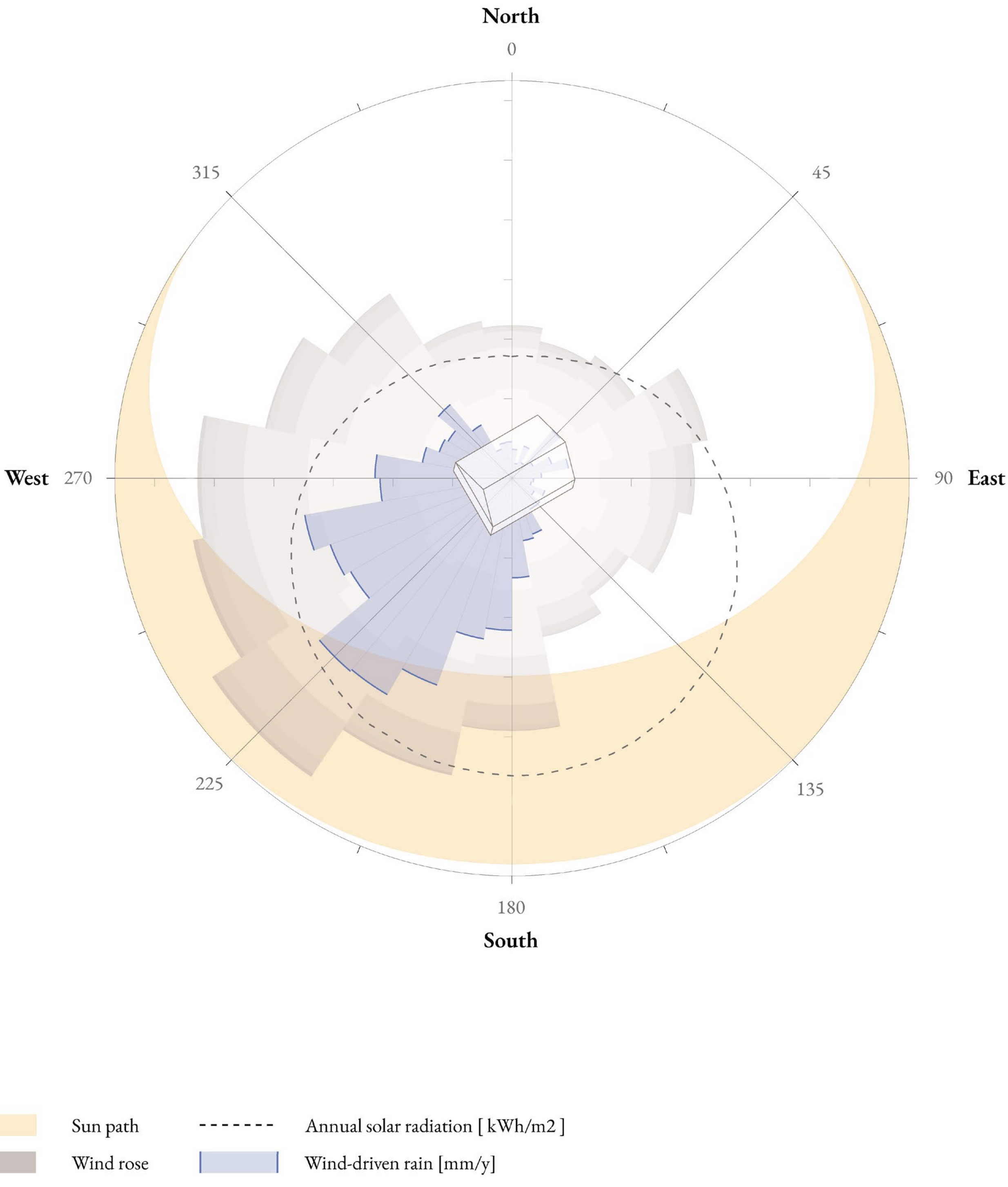


Fig. 48. Climate map for Lauwermeer National Park. Combined diagram of wind-driven rain (WDR), wind rose, solar radiation and sun path. Created by the author.

5.2. Conclusions

Wood weathering is a natural process which untreated timber undergoes as soon as it is exposed to the external environment. Although wood weathering is well studied as a chemical and physical process, there is a general lack of understanding of how natural weathering can be effectively employed as part of timber architecture design. This research, primarily based on a literature review, contributes to the positive perspective on timber weathering rather than an undesired and problematic aspect. In contrast to previously conducted research on timber weathering, this study explores the topic in the context of the North Netherlands, taking into consideration local climate conditions.

The study identifies the effects of different design aspects influencing the weathering of untreated timber facades in the distinct climate and environmental conditions of the North Netherlands and the effects of weathering on the building's appearance. There are three main categories of design discussed throughout the study: position relative to the cardinal direction, cladding design, and architectural design and detailing.

The relationship between the cardinal direction of the facade and the weathering process is highly dependent on local climate conditions. The findings are based on the translation of experiments carried out in Trondheim (Hirche, 2014; Rüther, 2011) through the comparison of climate maps, which include data on wind-driven rain and solar radiation. The results show that west and south-facing facades are subject to the most severe weathering, developing the dark grey colour the fastest. The east-facing facade is more prone to develop a dark brown colour over time.

Cladding design is a complex factor as it includes a large variety of cladding types which can be modified and combined according to the architect's preferences. Four common cladding types were discussed: horizontal cladding, vertical cladding, horizontal cladding with overlapping elements, and overlapping shingles cladding. As a general conclusion, cladding with non-overlapping elements develops more even colour throughout the weathering process, on the other hand cladding with overlapping elements allows for more complex colour pattern development.

Architectural design and detailing play an important role in the way buildings weather. Based on the Zimmer et al. report (2022), there is a set of design factors identified in this study, such as facade tilting, cantilevered elements, types of fixings and joints etc. Each of them has a specific influence on the colouration of the facade over time. Some of those factors, like ground-level cladding design, apart from the possible visual effects also relate to the service of life aspect.

As a general conclusion there is a diagram composing different design strategies and important considerations regarding untreated facade weathering is provided in the Conclusion chapter. It summarizes general design suggestions and aspects in relation to the cardinal orientation of the facade. While developed specifically as a base for the design stage of the graduation project "Designing with Weather" the diagram together with the research as a whole can be as an information tool for architects, craftsmen or others interested in the use of untreated wooded cladding in the Netherlands.

For a more location-specific focus, future research could delve into visual examples from the North Netherlands. This entails on-site exploration of local structures with untreated timber cladding, documenting their evolution over time and highlighting the region-specific challenges and opportunities. Additionally, gathering insights from locals about untreated timber facades would improve understanding of social and cultural influence and enhance the applicability of findings and recommendations to the specific needs and aesthetic preferences of the local community.

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6.2. List of Figures