Moisture safety of tall timber facades

Joakim Norén, Anna Pousette, Karin Sandberg

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Abstract

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The main purpose of the project was to facilitate safe design of sustainable and cost-effective solutions for wood facades of high-rise buildings. Studies have been carried out of different designs of the wall itself and of different details in the wall. Direct and indirect consequences of moisture damage have been considered but mainly risk of mould or decay. Façade details with high risk were identified e.g. window and balcony, and the types of damage that may occur, and what the consequences may be. Based on this, some damage scenarios were selected where detailed solutions were analysed more carefully. Details were also compared with modified designs with improvements such as addition of a sealing strip or plate covering. LCA and LCC have been calculated for some damage scenarios to show consequences of damages and the importance of well-executed designs and details.

Key words: timber facades, tall facades, moisture safety, wood moisture, damage scenarios, LCA, LCC
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1 Introduction

1.1 Goal and scope

This report is part of the project “Tall timber facades” with partners from Germany, Norway, France and Sweden and funded under the European WoodWisdomNet research programme. The main objective of the project “Tall timber facades” was to facilitate safe design of sustainable and hence cost-effective design solutions for the building envelope, tall timber facades, by the combination of existing best-practice with a risk-based concept. This report refers to some of the Swedish work.

A significant number of multi-storey timber office and housing projects have been and are currently developed all over Europe. To preserve and develop the chances on the market, wood construction must be reliable, durable, flexible and strong in off-site production/prefabrication. To fulfil most of these requirements a prolonged moisture-safety is necessary, which is in the focus of this project.

With an increasing height of timber buildings, the challenge is growing to provide moisture-safe conditions for the expected lifetime of building envelopes. Tall buildings are particularly exposed to high wind pressures combined with driving rain. Compared to fire safety and static demands, the risk of moisture damages today is often underestimated in planning, building processes, and quality management.
2 Moisture related damages in facades

2.1 Consequences of moisture

Consequences that have been discussed in the project are moisture related; i.e. excessive moisture content in the façade materials or even the presence of free water in the façade. The associated consequences, grouped into direct and indirect consequences, are shown in figure 2.1.

The input parameters to simulate moisture and failure modes in a construction are climate, wind, rain, temperature, initial moisture, building moisture, and all the material layers of the facade.

Direct consequences of moisture can be mould, blue stain, decay, and façade deterioration. This will indirectly affect the strength, deformation, insulation, aesthetics, or air quality. This may in turn lead to increased environmental impact and costs from replacement, repair, etc.

The climate and thus the moisture load vary between countries and also between regions within a country. This means it becomes more important to be careful about details and perhaps choose a more moisture safe solution, for example, on the west coast of Sweden than in northern Sweden.

The project was complex with several constructions and damage scenarios, and the focus was on the analysis of facades with regard to mould and rot. Different performances have been compared and their consequences, costs and environmental impact have been studied.

![Figure 2.1. Input and output parameters for calculations of direct and indirect consequences of moisture](image-url)
Failure modes can be analysed based on simulation results of moisture in the exposed facade. Consequences are based on empirical scale or by expert guess. The type and extent of the consequences has a direct influence on related costs, environmental impacts and other indirect consequences.

Mould and decay are serious consequences of moisture in a building and are described in more detail in chapters 2.2 and 2.3.

2.2 Mould

Mould is caused by excessive humidity in wooden constructions and grows on the surface of wood. It can affect aesthetics of a surface and the air quality in the building. Mould is a very complex biological phenomenon, which is highly dependent of the interrelation between humidity, temperature and time; including fluctuating conditions, the level and duration of favourable/unfavourable conditions together with their sequence, absorption, desorption and condensation processes. The material characteristics also affect mould including sapwood and/or heartwood, surface quality, finish system and wood treatment, and drying schedule. A schematic overview of the mould growth governing factors for wood-based materials is presented in figure 2.2. The assessment of what is classified as mould damage may vary and there are different models for assessing mould.

In order to represent the complex interaction between many factors influencing mould, there are models representing mathematically the mould growth through specified time duration and have found their application in the building engineering field. WUFI® is a computer program often used to analyse moisture in constructions and includes some different moisture and mould models.

![Figure 2.2 Mould growth governing factors [1]](image)
2.3 Decay

Decay is caused by decay fungi that grow through the wood cells and release enzymes that break down the wood components which they metabolize as food. This results in loss or significant reduction of many of the wood properties, such as toughness and strength.

The succession of microorganisms in the decaying of wood is very complex and variable. Different fungi need different conditions in terms of nutrients, temperature and water to establish themselves on wood and survive [2, 3]. The structural constituents of wood species as well as chemical composition and type and amount of extractives influence the rate of decay from particular decay fungi [4, 5].

During decay, the wood changes chemically. These changes manifest as visible discolouration and texture changes as the breakdown proceeds. Various groups of fungi attack the wood cell-wall constituents in different ways. Most common are brown rot, white rot and soft rot degradation. Based on the visible changes in wood, various methods for detecting and evaluating decay have been developed, visual evaluation, image analysis, microscopic evaluation, pick or splinter test, density and mass loss and strength test [6].

All decay fungi attacks on wooden elements will influence the mechanical resistance. Major effects on strength occur very early in decay, below 5-10 % mass loss. Calculation of the mechanical resistance of a timber part must be done with a reduced cross-section, the section without decay.

Several factors have effect on fungal decay and the strength loss (compare figure 2.2 for mould fungi):

- Wood temperature
- Moisture content, min. threshold for onset of decay often below fibre saturation point
- Exposure time
- Type of fungus, brown rot, white rot, soft rot, etc. – different fungus species
- Type of wood species, pine, spruce, beech, oak, etc.
- Strength property

2.4 Engineering design guideline from project Woodbuild

Service life of wood in outdoor above ground applications was studied in a Swedish national research project called Woodbuild and an Engineering design guideline was presented [10]. The principle for the performance-based service life design model was described in terms of climatic exposure on one hand and resistance of the material on the other hand based on dose-response models for above-ground decay [11]. Exposure was described as a function of global and local climate, component design and surface treatment in a general way. The resistance of different types of materials was expressed in terms of response to a quantified and standardized micro-climate. The design model was related to a limit state of onset of fungal decay. In the model an annual exposure
dose is calculated with several factors describing the climate and structure. Relationship between dose and mean decay rating was established, see figure 2.3.

The standard EN 350 [7] puts the natural durability of wood into five classes, where 1 is very durable and 5 is not durable. Classification is determined in the field using specimens in ground contact according to EN 252 [8]. Classification is made with a rating system for the assessment where 0 is no attack of fungi and 4 is failure of the specimen.

![Figure 2.3 Relationship between dose and mean decay rating (DR) according to EN 252 [9]](image)

The effect of microclimate conditions as influenced by the detailed design is described by a factor $k_{ES}$. For design detailing related to cladding, the ratings of $k_{ES}$ are described in figure 2.4 and table 2.1. The classification is based on ventilation of the back of the cladding and of the degree of protection of wood end grain. For durability aspects of a cladding it was suggested that the presence of an air gap is most important as longs as it is at least 5 mm. This corresponds to $k_{ES}=1$.

![Figure 2.4 Categories of ventilation and air space of the back of the cladding [10]](image)
### Table 2.1. Ratings of details for cladding boards and panels

<table>
<thead>
<tr>
<th>Rating</th>
<th>Ventilation</th>
<th>End grain protection</th>
<th>$k_{E6}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Excellent</td>
<td>Fully ventilated</td>
<td>With gap and end grain sealed or covered</td>
</tr>
<tr>
<td>2</td>
<td>Good</td>
<td>Limited ventilation</td>
<td>With gap without end grain protection</td>
</tr>
<tr>
<td>3</td>
<td>Medium</td>
<td>Not ventilated with air space</td>
<td>1.2</td>
</tr>
<tr>
<td>4</td>
<td>Fair</td>
<td></td>
<td>Without gap but sealed</td>
</tr>
<tr>
<td>5</td>
<td>Poor</td>
<td>Not ventilated and no air space</td>
<td>Without gap and unsealed</td>
</tr>
</tbody>
</table>
3 Experiences of damages in timber facades

Experiences of moisture damages in wooden buildings from timber house manufacturers and insurance companies was investigated. The purpose was to study the occurrence and extent of damage and assess risks with different designs. These experiences of real cases were then used together with expert knowledge to create damage scenarios to study the consequences in LCA and LCC calculations.

3.1 Experiences from timber house manufacturers

A questionnaire about experiences of damages in facades was sent out to some timber house manufacturers in Sweden. There were answers from five companies. The house manufactures build mostly 1- and 2 storey houses, but three of the companies answered that they also build tall houses today with more than 2 stories (up to 4 or 7 stories).

Summary of their answers about damages in facades:
- Most of the companies have had some cases of damages of facades due to water penetration from outside.
- Both ventilated and non-ventilated claddings were damaged.
- There was always a second defence layer behind the first layer (cladding) of the façade.
- It was specific details in the structure that caused the damages due to outside penetration. The main cause was horizontal interruptions (balcony, loggia, etc.), some were caused by openings (windows, doors, etc.), and there were also a few damages due to penetrations (pipes, cables, etc.).
- There were fewer experiences of damages from indoor moisture. It was usually due to convection, bathroom or shower (diffusion).

The companies had positive experiences from ventilated wooden facades and also from plaster facades on ventilated plaster base sheet and applied on well insulated timber frames. One company mentioned that vertical wood panel was preferred. Second defence layer (two stage sealing) worked generally well.

3.2 Experiences from insurance company

Within the project, a review of errors and damages to facades was carried out by an insurance company that provides assurances for errors/damages that occur during the first ten years after completion of the building [12]. The review included 185 damage cases that occurred during the period 2009-2016. Most houses were 1- or 2 storey timber frame houses with wood or plaster cladding.

Causes of damage in facades are shown in figure 3.1. The main causes were shortcomings in window flashings and other metal sheets and their connections to the facade in
general, mainly around the window. Other damages reported were more evenly distributed, see figure 3.1. Most of the damages were discovered during the first 8 years.

![Figure 3.1. Main cause of damages in facades](image)

Three examples of damage cases are described in chapters 3.2.1 – 3.2.3. Failure and consequences as well as risk reducing measures are described.

### 3.2.1 Example of damage case – window connection

In this example of a damage case the building is a two-family house with two floors and an attic. The building has a light frame structure with studs of structural timber. The exterior walls have a wood cladding and the inside is covered with gypsum plasterboards and the insulation is glass wool.

The building was completed in 2006 and problem with water leakage at window connections was detected already during the first two years. After several failed attempts to fix the problems described, the outer wood panel was removed 2009. The damaged insulation was replaced, and a new wind barrier and wood panel were mounted. Window flashings above the windows were also installed as improvement. Later that year the attic was converted, and more windows installed. Despite all the measures the same problem
of water leakage at windows occurred. Water leakage was observed when the window linings swelled. After the window sill was removed, it was found that the insulation was very wet, see figure 3.2.

At the inspection, it was found that water which had penetrated behind the wooden panel and at the window connection was not drained through the air gap. Instead, the water followed the wind barrier foil further into the wall through holes or incorrectly performed overlapping and moistened the wooden studs and sills. It was found that the problem was caused by the sill insulation sticking out into the air gap and preventing water drainage and ventilation. Water running down in the air gap continued instead under the sill and further into the construction.

Besides the problems with the air gap, it was found that the installation of the fresh air vent in the wall was poorly executed, see figure 3.3. The pipe members were not compressed together, and the pipe slanted inward resulting in water leakage.

Failure and Consequences
Consequence of the water ingress in the window connections was damage in large parts of the wall next to the windows. Materials in the wall had to be replaced. Cost of repair was 11915 €.

Risk reducing measures
Correct installation of wind barrier that secures drainage of the air gap can avoid problems.
3.2.2 Example of damage case – window-floor connection

This case describes problems with moisture damage in the parquet floor next to windows, see figure 3.4. The parquet had become discoloured and moisture measurements showed high moisture content in the floor close to the window.

An inspection of the damage showed that the filling material in the ground next to foundation was too dense which prevented drainage. This resulted in a moist concrete slab. The ground level was also too high, and water had been leaking in between the window frame and the concrete slab which indicated an insufficient sealing.

**Figure 3.4 Moisture damage in parquet next to window**

**Figure 3.5 Removal of decking to replace the landfill closest to the window. New sealing between the window frame and foundation.**

**Failure and Consequences**
There was water ingress in connection between lower window frame and foundation. The consequence was moisture damage in lamella parquet. Cost of repair was 2480 €.

**Risk reducing measures**
Improper filling was removed, and the foundation could dry out, see figure 3.5. The foundation was then isolated with a moisture- and thermal insulation (Isodrän board). New drainage was used. To avoid damages, a proper sealing between the window frame and the foundation was installed.

3.2.3 Example of damage case – window connection

This damage case is from a two-family house with two floors. The building has a light frame structure of structural timber and the exterior walls have a wood panel cladding. The inside lining is gypsum plasterboard and the insulation is mineral wool. The windows are placed flush with the facade without any flashings or similar protection.
Problems with leaking windows started shortly after the final inspection of the house and were directly corrected by the builder. In September 2015 there were new problems with water leakage in a number of windows during heavy rain. Visible interior damages from the leak were:

- Water damage on the parquet floor below the window, see figure 3.6.
- Five leaking windows and a leaking door.
- Moisture-damage over window in a bathroom, see figure 3.7.

An inspection of the damages indicated several causes of leak of water. The windows that leaked were all in an open and exposed position in the facade. Window connections in the facade had a poor design without an upper flashing and no external window linings which made it easy for water to get into the wall between the front panel and the window, see figure 3.8 and 3.9. The window sill flashing was in one case too short and water could leak between the flashing and the panel.

Window vents in figure 3.8 slanted upward towards the outside and in rain combined with wind, water could leak through the valve and further down on the floor or window sill. Moisture damage was found in two places in the parquet flooring caused by water that had entered through the window frame and into the wall. Microbial growth was found on the rag paper under the parquet, see figure 3.6.
Failure and Consequences
There was water ingress in the connection between window frame and wall, and leakage through the window vent. Moisture damage was found in lamella parquet. The consequence was replacement of water-damaged gypsum plasterboard, insulation and vapour barrier at the window connections. Dehumidification and fungicide treatment of wood was made before the restoration of the wall, and replacement of damaged multi-layer boards of the parquet floor was made. Cost of repair was 16660 €.

Risk reducing measures
Supplementary sealing strips at the top of the window vent to reduce the risk, and installation of an upper and lower flashing at the windows.
4 Risk areas and damage scenarios

4.1 Analysed wall structures

Best practice constructions and details that fulfil all other requirements on facades, such as strength, acoustics, fire and insulation were studied. These examples represent some possible alternatives of frame, panels and insulation etc. and have been evaluated with respect to durability, replacements, and maintenance and life cycle impact (LCA) and costs (LCC). Two typical walls were studied; one was a CLT structure (see chapter 4.1.1) and the other a wood frame structure (see chapter 4.1.2).

4.1.1 CLT structure

Martinsons’ building system for high buildings is based on components in CLT (Cross-Laminated Timber) [13]. The construction parts in CLT are prefabricated and can be offered with interior covering and facade covering and also with integrated installations. The factory environment and the assembly system on-site with a weather protection system increase the possibility for a good and dry construction. Figure 4.1 and table 4.1 presents an example of façade.

![Figure 4.1. Exterior wall with CLT structure.](image)

<table>
<thead>
<tr>
<th>Functional layers</th>
<th>Building material</th>
<th>Thickness [mm]</th>
<th>Density [kg/m³]</th>
<th>λ [W/mK]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>external</strong></td>
<td>A  Glulam Panel</td>
<td>25</td>
<td>410</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>B  Battens</td>
<td>22</td>
<td>410</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>C  Air gap</td>
<td>22</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>D  Waterproof breather foil</td>
<td>0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>core</strong></td>
<td>E  Plywood</td>
<td>12</td>
<td>500</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>F  Plastic distance</td>
<td>70</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>G  Mineral wool</td>
<td>70</td>
<td>30</td>
<td>0.036</td>
</tr>
<tr>
<td></td>
<td>H  Battens</td>
<td>140</td>
<td>410</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>I  Mineral wool</td>
<td>70+70</td>
<td>30</td>
<td>0.036</td>
</tr>
<tr>
<td><strong>internal</strong></td>
<td>J  Vapor barrier</td>
<td>0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>K  CLT</td>
<td>120</td>
<td>400</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>L  Gypsum board type F</td>
<td>15.4</td>
<td>825</td>
<td>0.22</td>
</tr>
</tbody>
</table>
4.1.2 Wood-frame system with structural timber

Moelven is a producer of modular buildings [14]. Production takes place in factories in the form of prefabricated apartments where the modules are delivered ready for assembly to the construction site. Manufacturing takes place indoors and good control of the construction process at the site increase the possibility for a good and dry construction. Figure 4.2 and table 4.2 presents an example of façade.

![Figure 4.2. Exterior wall with wood frame structure](image)

Table 4.2. Materials in exterior wall wood frame structure

<table>
<thead>
<tr>
<th>Functional layers</th>
<th>Building material</th>
<th>Thickness [mm]</th>
<th>Density [kg/m³]</th>
<th>λ [W/mK]</th>
</tr>
</thead>
<tbody>
<tr>
<td>external</td>
<td>A Plaster</td>
<td>8</td>
<td>2000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B Cement board</td>
<td>12</td>
<td>1280</td>
<td>0,35</td>
</tr>
<tr>
<td></td>
<td>C Battens</td>
<td>28</td>
<td>460</td>
<td>0,12</td>
</tr>
<tr>
<td></td>
<td>D Mineral wool</td>
<td>30</td>
<td>60</td>
<td>0,032</td>
</tr>
<tr>
<td></td>
<td>E Ext Gypsum board</td>
<td>9</td>
<td>737</td>
<td></td>
</tr>
<tr>
<td>core</td>
<td>F Battens</td>
<td>195</td>
<td>460</td>
<td>0,12</td>
</tr>
<tr>
<td></td>
<td>G Mineral wool</td>
<td>195</td>
<td>19</td>
<td>0,036</td>
</tr>
<tr>
<td>internal</td>
<td>H Vapor barrier</td>
<td>0,11</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>I Gypsum board</td>
<td>13</td>
<td>720</td>
<td>0,22</td>
</tr>
<tr>
<td></td>
<td>J Gypsum board</td>
<td>13</td>
<td>720</td>
<td>0,22</td>
</tr>
</tbody>
</table>
4.2 Risk areas in timber facades

Damage scenarios are described for the most frequent damages in the defined risk areas of the façade in chapter 4.4.1-4.4.5. A description of the extent of damage and the measures needed to restore the function of the structure are also included.

The extent of the damage is often complex and depends on several parameters such as moisture load, time of exposure, risk area (component/connection), etc. Typical risk areas in a building are shown in figure 4.3. Depending on the wall construction and its components, there are natural borders that can prevent or reduce the spread of water and moisture inside the wall e.g. moisture barriers, dense materials, studs and air gaps. Based on experience from manufacturers and data from insurance companies, an assessment of reasonable damage scenarios for window connection, balcony connection, and roof-wall connection were performed. The aim was to create scenarios that show different levels of damage to the components and the direct or indirect consequences that it may cause, for example, which parts must be repaired or replaced. In the scenario approach three damage levels are presented for each risk area. Various measures of the damage can be used and an appropriate or sufficient measure is offered.

Improved solutions of the details with increased moisture safety are also presented in chapter 4.5. These will lead to a more robust design with secure installation of the component under construction and reduced risk and maintenance during the building lifecycle.

Three levels of damage, small, medium and extended damage, were analysed. Based on the material and energy flows for repair or replacement, the environmental impact over the building life cycle was calculated using the modular system in accordance with EN 15804 [15]. Life cycle cost was calculated with the same assumptions. In the approach with improved details the analysis shows the potential benefits of using a robust design.

Damage detected and fixed during construction time is typically a visible damage, caused by moisture problems during construction (for example poor moisture protection during transport, storage or installation). Actions are paid by the builder.
Damage detected during the building life after construction can for example be visible moisture or deformation or a bad smell. It can be caused by errors during planning/design (difficult location, wrong choice of construction or material) or during construction time (poor protection, improper performance, exchange of materials, etc.). Measures are paid by builders during guarantee period 2-5 years, and by insurance company or owner during the rest of the lifecycle.

Risk of damage should be reduced by careful control schedules of design and construction [16] to avoid errors during planning and construction. It is important to ensure sufficient drying out of building moisture, and that no moisture damaged materials have been built in. Good maintenance work of the building during the life is also essential to avoid the risk of moisture damage. At unforeseen events, as breakage on the tap water pipeline, or changed conditions for the building in some way, such as altered use or climate change, it is important with proper investigations of the structure.

4.3 Measure of damages

When there are signs of moisture damage in the facade, the wall must be opened to assess the extent of damage and appropriate measures. This means that materials must be removed and then replaced with new ones. The consequence of a leakage will be to remove all moist materials and moisture damaged materials. After that the moist structure must be dried using dehumidifier and the wall can then be rebuilt and restored. If there is decay in structural parts they are usually kept and supplemented if it is difficult to unload and replace, for example bearing studs.

Main steps of measure of damages:
− Open up the facade from inside or outside
− Remove insulation and other moist materials
− Dehumidify materials for 1-4 weeks
− Replace damaged materials with new ones

Different damage scenarios were studied and analysed as to how water from a leakage might spread in the structure and cause moisture damage. Scenarios for three different extents of moisture damage, small damage, medium damage and extensive damage are illustrated and described for window connection, balcony door connection and roof connection for CLT-structure and timber frame structure in chapters 4.4.1-4.4.5.
4.4 Analysed details

The analysis with damage scenarios included three detailed connections, window connection, door/balcony connection and roof-wall connection. Windows and balcony connections are the risk areas in the façade which have the most frequent damages. Roof-wall connection was considered interesting to study because there can be snow blowing in the wind through the connection and then causing problems when it melts.

In Sweden, the use of CLT as a frame in multi-family houses has increased. However, it can be regarded as a fairly new building system and therefore, there are so far no or very few reports of moisture problems in facades and detail connections. The technical design of the wall and its connection details are proven by the manufacturers and have not shown any problems. For detailed connections in the CLT construction, the scenarios are that damage occurs mainly in the materials outside the vapour barrier and the CLT panel.

4.4.1 Window connection in CLT structure

In the analysed CLT structure, the window is located at the centre of the cross section of the wall right next to the CLT panel, see figure 4.4. In case of a leakage in the lower part of the window connection, the propagation of water is assumed to follow the timber studs and material layers in the outer part of the wall as shown in figure 4.5. Table 4.3 shows the spread of moisture across the wall as well as normal repair measures. Damage to the CLT wall is usually repaired from the outside which usually requires scaffolding. Exceptions are at balconies and galleries. Replacement of CLT elements is avoided as this requires more comprehensive measures, such as unloading etc. In case of more widespread damage, scenario 3, there is also assumed to be decay at the lower ends of the studs closest to the window.

Figure 4.4. Window connection in wall with CLT elements
Figure 4.5. Scenarios for three different extent of moisture damage in window connection in wall with CLT elements.

Table 4.3. Scenarios for the damage spread across the wall in figure 4.5.

<table>
<thead>
<tr>
<th>Damage scenario</th>
<th>Measure of damage</th>
<th>Replaced materials (area, m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1 - small damage</td>
<td>- Open up the facade from outside</td>
<td>- Mineral wool 1 x 0.3 m</td>
</tr>
<tr>
<td></td>
<td>- Remove insulation next to the window sill</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Dehumidify materials for 7 days</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Replace damaged materials</td>
<td></td>
</tr>
</tbody>
</table>
### Scenario 2 - medium damage

- **Open** up the facade from outside
- **Remove** insulation under the window sill
- **Dehumidify** materials for 14 days
- **Replace** damaged materials

- Battens
- Mineral wool 0.8 x 1 m
- Mineral wool 2 x 0.6 x 0.3 m

### Scenario 3 - extensive damage

- **Open** up the facade from outside
- **Remove** insulation to window beneath
- **Dehumidify** materials for 28 days
- **Replace** damaged materials

- Water proof breather foil
- Mineral wool, 1.5 x 1 m
- Mineral wool, 1.5 x 0.6 m
- Mineral wool, 2 x 0.6 x 0.3 m
4.4.2 Window connection in timber frame structure

The window connection in the frame structure is shown in figure 4.6. The window is placed flush with the outside of the studs. In this case the wall is part of a modular system, and the figure also shows the detailed design of the modular joint between two floors.

Moisture damage below the window is assumed to initially spread under the window between the studs on both sides of the window, see figure 4.7. Down the sill, the moisture will spread laterally. In case of more extensive damage, the ceiling and wall of the underlying floor will be involved. In this case, even rot is assumed in the lower part of the studs closest to the window. Table 4.4 shows the spread of moisture across the wall as well as normal repair measures. Damage to the structural frame wall is usually repaired from the inside. If there is decay in load bearing studs, additional studs will be installed as reinforcement after drying of damaged parts. Replacement of load bearing studs is normally avoided due to risk of deformations in the structure.

![Figure 4.6. Window connection in timber framed wall.](image)

![Figure 4.7. Scenarios for three different extent of moisture damage in window connection in wall with timber frame structure.](image)
Table 4.4. Scenarios for the damage spread across the wall in figure 4.7.

<table>
<thead>
<tr>
<th>Damage scenario</th>
<th>Measure of damage</th>
<th>Replaced materials</th>
</tr>
</thead>
</table>
| Scenario 1 - small damage | - Open up the facade from inside  
- Remove insulation under the window  
- Dehumidify materials for 7 days  
- Replace damaged materials | - Gypsum board 1 x 0.8 m  
- Vapor barrier 1.2 x 1 m  
- Mineral wool, 1 x 0.5 m |
| Scenario 2 - medium damage | - Open up the facade from inside  
- Remove insulation under the window  
- Dehumidify materials for 14 days  
- Replace damaged materials | - Gypsum board 1 x 0.8 m  
- Vapor barrier 1.2 x 1 m  
- Mineral wool, 1 x 0.8 m  
- Mineral wool 2 x 0.6 x 0.3 |
| Scenario 3 - extensive damage | - Open up the ceiling in underlying apartment  
- Remove the floor insulation next to the exterior wall  
- Open up the wall from inside  
- Remove wall insulation  
- Dehumidify materials for 28 days  
- Replace damaged materials  
- Ceiling | - Gypsum board in ceiling 3.4 x 0.5 m two layers  
- Mineral wool, 3.4 x 0.5 m  
- Wall  
- Gypsum board 2.2 x 0.8 m  
- Mineral wool 2.4 x 1 m  
- 2 extra wood studs, 2.5 m  
- Gypsum boards 1.2 x 0.4 m  
- Mineral wool 2.4 x 0.5 m |
4.4.3 Balcony connection in CLT structure

The balcony connection with a balcony door is shown in figure 4.8. The door is placed flush with the outer insulation layer in the wall. Moisture damage below the door is assumed to spread in the outer material layers outside the vapour barrier, see figure 4.9 and table 4.5. Moisture-damaged materials are replaced from outside of the wall.

![Figure 4.8. Balcony connection – CLT structure](image)

![Figure 4.9. Scenarios for three different extent of moisture damage in balcony and door connection in CLT structure.](image)
Table 4.5. Scenarios for the damage spread across the wall in figure 4.9.

<table>
<thead>
<tr>
<th>Damage scenario</th>
<th>Measure of damage</th>
<th>Replaced materials</th>
</tr>
</thead>
</table>
| **Scenario 1 - small damage** | - Open up the façade from outside  
- **Remove** the insulation next to the door sill  
- **Dehumidify** materials for 7 days  
- **Replace** damaged materials | - Mineral wool, 1 x 0,5 m, one layer?  
- Wind barrier 1 x 0,5 m |
| **Scenario 2 - medium damage** | - Open up the façade from outside  
- **Remove** the insulation  
- Dehumidify materials for 14 days  
- **Replace** damaged materials | - Mineral wool, 1.8 x 0,8 m, two layers?  
- Wind barrier 2 x 0,6 m |
| **Scenario 3 - extensiv damage** | - Open up the façade from outside  
- **Remove** the insulation  
- Dehumidify materials for 28 days  
- **Replace** damaged materials | - Mineral wool, 1.8 x 0,8 m, three layers?  
- Wind barrier 2 x 0,6 m |
4.4.4 Balcony connection in timber frame structure

The balcony and balcony door connection in the timber frame structure is shown in figure 4.10. The door in this case is located flush with the outside of the timber studs. The scenarios for three different extent of moisture damage in the balcony and door connection is shown in figure 4.11. If damage occurs the water will spread along the vapour barrier and further down in the wall under the balcony door. The moisture damage is often visible in the ceiling and along the window reveals in the underlying floor, see table 4.6.

Figure 4.10. Balcony connection – timber frame elements

Figure 4.11. Scenarios for three different extent of moisture damage in balcony and door connection.
Table 4.6. Scenarios for the damage spread across the wall in figure 4.11.

<table>
<thead>
<tr>
<th>Damage scenario</th>
<th>Measure of damage</th>
<th>Replaced materials</th>
</tr>
</thead>
</table>
| Scenario 1 - small damage| - **Open** up the ceiling in underlying apartment  
- **Remove** the floor insulation next to the exterior wall  
- **Dehumidify** materials for 7 days  
- **Replace** damaged materials | - Gypsum board in ceiling 1 x 0.5 m two layers  
- Mineral wool, 1 x 0.5 m |
| Scenario 2 - medium damage| - **Open** up the ceiling in underlying apartment  
- **Remove** the floor insulation next to the exterior wall  
- **Dehumidify** materials for 14 days  
- **Replace** damaged materials | - **Ceiling**  
- Gypsum board in ceiling 2.2 x 0.5 m two layers  
- Mineral wool, 2.2 x 0.5 m  
- **Wall**  
- Plaster 0.8 x 1.0 m  
- Fiber cement board 0.8 x 1 m  
- Battens  
- Mineral wool board 0.8 x 1 m  
- Gypsum board ext 0.8 x 1 m  
- Mineral wool 0.7 x 1.0 m |
| Scenario - extensiv damage| - **Open** up the ceiling in underlying apartment  
- **Remove** the floor insulation next to the exterior wall  
- **Open** up the wall from outside  
- **Remove** wall insulation  
- **Dehumidify** materials for 28 days  
- **Replace** damaged materials | - **Ceiling**  
- Gypsum board in ceiling 3.4 x 0.5 m two layers  
- Mineral wool, 3.4 x 0.5 m  
- **Wall**  
- Plaster 0.8 x 1.0 m  
- Fiber cement board 0.8 x 1 m  
- Battens  
- Mineral wool board 0.8 x 1 m  
- Gypsum board ext 0.8 x 1 m  
- Mineral wool 0.7 x 1.0 m  
- 4 extra wood studs, 2.5 mm  
- 4 gypsum boards 1.2 x 2.5 m  
- Mineral wool 2.4 x 1.2 m |
4.4.5 Roof-façade connection in timber frame structure

The analysis of roof-façade connection has only been implemented for timber frame system because CLT system often has an attic and roof structure of structural timber. The roof–façade connection is shown in figure 4.14. The moisture damage in this case is caused by snow blowing in through the ventilation gap at the eaves. Three scenarios with different extent of moisture damage have been analysed, see figure 4.15. This was primarily to get an estimate of damage costs but also to compare with an improved detail solution of the eaves. Due to the design of the connection the moisture damage mainly includes the materials in the roof and attic structure, see table 4.7.

![Figure 4.14. Roof-façade connection in timber frame system.](image)

![Figure 4.15. Scenarios for three different extent of moisture damage in façade due to blowing snow leaked into roof-façade connection.](image)
### Table 4.7. Scenarios for the damage spread across the wall in figure 4.15

<table>
<thead>
<tr>
<th>Damage scenario</th>
<th>Measure of damage</th>
<th>Replaced materials</th>
</tr>
</thead>
</table>
| **Scenario 1 - small damage** | - Open up the roof and the wall from the inside  
- Remove the insulation next to the roof-façade connection  
- Dehumidify materials for 7 days  
- Replace damaged materials | **Roof**  
- Mineral wool, 1.2 x 0.3 m  
- Vapour barrier 1.2 x 0.3 m  
**Wall**  
- Gypsum board 1.2 x 0.5 m  
- Mineral wool, 1.2 x 0.3 m  
- Vapour barrier 1.2 x 0.3 m |
| **Scenario 2 - medium damage** | - Open up the roof and the wall from the inside  
- Remove the insulation next to the roof-façade connection  
- Dehumidify materials for 14 days  
- Replace damaged materials | **Roof**  
- Mineral wool, 2.4 x 0.3 m  
- Vapour barrier 2.4 x 0.3 m  
**Wall**  
- Gypsum board 1.8 x 0.6 m  
- Mineral wool, 1.8 x 0.3 m  
- Vapour barrier 1.8 x 0.6 m |
| **Scenario 3 - extensive damage** | - Open up the roof and the wall from the inside  
- Remove the insulation next to the roof-façade connection  
- Dehumidify materials for 28 days  
- Replace damaged materials | **Roof**  
- Mineral wool, 1.8 x 0.3 m  
- Vapour barrier 1.8 x 0.3 m  
**Wall**  
- Gypsum board 2.4 x 0.6 m  
- Mineral wool, 2.4 x 0.6 m  
- Vapour barrier 2.4 x 0.6 m  
**Ceiling**  
- Gypsum board 2.4 x 0.5 m  
- Mineral wool, 2.4 x 0.3 m  
- Batten 2.4 m |
4.5 Improvement of details - examples

**Window Connection**
A standard connection usually works well, see figure 4.16. On more exposed facades though, an improved connection with a steel profile behind reveal can provide increased safety against leakage, see figure 4.17. The steel profile means additional materials and thus more environmental impact and increased cost, but this will be less compared to avoiding damage.

*Figure 4.16. Standard connection of window in wall*

*Figure 4.17. Improved connection with steel profile behind reveal*

**Balcony Connection**
An improved connection at the balcony can be obtained with a sealing layer, as a second protection layer on top of the sill and on the side of the wall, see figures 4.18 and 4.19. The increased environmental impact and increased cost is little compared to damage.

*Figure 4.18. Standard connection of balcony and balcony door.*

*Figure 4.19. Improved connection with a sealing layer, green line, as second defence on top of the sill and on the side of the wall.*
**Roof-façade Connection**

At the roof-façade connection the aim with an improvement is to prevent rain and snow from blowing into the loft and thus causing moisture damage. Different ways to seal the roof connection are possible, see figure 4.20. Long eaves combined with a covering with boards or with a snow tube in the air gap should work well and will result in less environmental impact or cost compared to damage.

<table>
<thead>
<tr>
<th>Short eaves ≤ 0.2 m and gutter outside façade. No wind deflector</th>
<th>Short eaves ≤ 0.2 m and gutter outside façade. Wood panel as wind deflector</th>
<th>Long eaves ≥ 0.5 m, gutter outside façade. No wind deflector.</th>
<th>Long eaves ≥ 0.5 m with snow tubes (PE) in air gap.</th>
</tr>
</thead>
</table>

*Figure 4.20.*

*Five different solutions of a roof–façade connection with different protection against wind driven rain or snow.*
5 LCA and LCC

LCA and LCC calculations can be used to evaluate the environmental impact and costs of moisture-related damages in the wooden facades over the building life cycle. The extent of water damage in the external wall can be difficult to describe and the amount of materials that are replaced can vary greatly. The approach is that the methodology for the analysis is based on the damage scenarios with different extent of moisture damage described in chapter 4.

5.1 Life cycle assessment (LCA)

A number of methodological choices have to be taken into account when an LCA is made. These choices can have a significant impact on the final result. The main methodological issues are the choice of functional unit, system boundaries and the type of data used. The functional unit becomes especially important when different studies are compared. Selections and assumptions about the system boundaries are often decisive for the outcome of an LCA. The quality of the results also depends on the choice of data.

How to perform calculations of the environmental performance of buildings is specified in the standard EN 15978 [17]. Furthermore, there is standard EN 15804 [15] which gives the product category rules (PCR) for all construction products and construction services. In these standards the building system boundaries are divided in modules (A, B, C, and D). These are in turn divided into sub-modules (A1, A2, ..., B1, B2, ..., etc.) Modules A1 to C4 covers the environmental impact that is directly related to activities that take place within the building system boundary, and describes the building’s life cycle, the so-called modularity. This means that the environmental impact of each module is presented separately e.g. from repair and replacement of materials in a wall due to moisture damage.

The environmental impact from indirect consequences caused by moisture damage to the facade can be related to module B3 and B4, that includes repair and replacement. Repair refers to the replacement of a broken component due to damage and replacement refers to replacement of a complete element due to damage.

LCA calculations of damages were performed for damage scenarios described in chapter 4. The calculation follows the modular set up of the life cycle stages in accordance with EN 15804 [15]. The inventory includes the following stages of the building life cycle:

- Product stage, A1-3
- Construction process, A4-5
- Use stage, B3 Repair and B4 replacement.

Due to missing data and other information about the processes, the inventory is not comprehensive for all stages. However, for the product stage module A1-3 and the repair module B3, most of the relevant data of the processes that have the biggest environmental impact are included in the inventory. These processes are:

- Production of new materials/component and ancillary materials
- Use of energy (machines for drying and heat during repair B3)
– Production and transport of wastage of materials during repair or replacement
– Transportation of new materials/components and ancillary materials.

The quality of the results also depends on the choice of data used in the LCA. Data must be representative of the materials and products that are included in the analysis. In the analysis of indirect impacts from moisture damage in the façade, primarily national average data or data from EPDs that are consistent with the product were used. In some cases, also specific national data have been used. Some EPDs may also be specific data for a product from one company.

The functional unit is the base for calculation of the material flows and environmental impacts over the products life cycle stages. For calculation of the indirect consequences of moisture damages in the facade, the functional unit was “a wall element with length 3 m and height 2.4 m including one window 1.2 m x 1.4 m or one balcony door 1.0 m x 2.1 m or one roof damage with length 1.2 m, and with a life span of 50 years”.

5.2 Life cycle cost (LCC)

Life-Cycle Cost (LCC) is used for assessing the cost performance of constructed assets and is described in the standard ISO 15686-5 [18]. The standard establishes terminology and methodology for life-cycle costing that should enable the use of LCC in the construction industry. Life-cycle costing is performed over a specified period of analysis.

LCA calculations of damages were performed for damage scenarios described in chapter 4. The costs from consequences caused by moisture damage to the façade can be related to repair and replacement of damaged materials in the same way as in the LCA calculations, see chapter 5.1. The quality of the LCC results depends on the choice of data used in the calculations. LCC analyses need current economic data from clients and the construction industry. It can be carried out at a coarse level using industry-average or standard data or at a detailed level based on specific estimates or predictions of component performance. Both generic data from Sektionsfakta® – ROT [19] and BKI Baukosten [20] and specific data assigned to a specific company or product was used.

The functional unit is the base for calculation of the material flows and costs over the products life cycle stages. For calculation of the indirect consequences of moisture damages in the facade, the functional unit was “a wall element with length 3 m and height 2.4 m including one window 1.2 m x 1.4 m or one balcony door 1.0 m x 2.1 m or one roof damage with length 1.2 m, and with a life span of 50 years”.

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6 Result of LCC and LCA

6.1 Life cycle assessment (LCA)

Climate impact is used to describe the environmental impact of the production of wall, maintenance and repair during service life. Calculation is based on a wall element with the area of 3 m x 2.5 m with a damage caused by window, balcony or roof connections in the wall. Three levels of damage, small, medium and extensive, are analysed. Only the impact of the wall materials is included, not the different components (windows, doors, etc.).

In figures 6.1-6.2 the relative environmental impact of the production of an exterior wall element with CLT structure and regular maintenance are presented, as well as the impact of moisture damages in window or balcony connection in the wall.

Based on the damage scenarios the climate impact of damage in the window connection is much lower than the impact of the production of the wall, see figure 6.1. This is mainly because the spread of water is limited in the wall and the damaged area is much smaller than the plain wall element area. Figure 6.2 shows climate impact for damages in a balcony connection with balcony door. This connection will result in a slightly higher impact than the window connection due to more materials involved.

Figure 6.1. Climate impact of damages in window connection in CLT wall according to chapter 4.4.1 compared to impact of production of wall construction and regular maintenance.
In figures 6.3-6.5 the relative environmental impact of the production of an exterior wall element with structural frame and regular maintenance are presented, as well as the impact of moisture damages in window, balcony and roof connection in the wall.

Based on the damage scenarios the climate impact of damage in the window connection is much lower than the impact of the production of the wall, see figure 6.1. This is mainly because the spread of water is limited in the wall and the damaged area is much smaller than the plain wall element. Figure 6.4 shows climate impact for damages in a balcony connection with balcony door. This connection will result in a slightly higher impact than the window due to more materials involved.

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Figure 6.4. Climate impact of damages in balcony connection in structural frame wall according to chapter 4.4.4 compared to impact of the production of wall construction and regular maintenance.

Figure 6.5. Climate impact of damages in roof-wall connection in structural frame wall according to chapter 4.4.5 compared to impact of the production of wall construction and regular maintenance.

6.2 Life cycle cost (LCC)

In figures 6.6-6.8 the costs of exterior structural frame wall and regular maintenance are presented (grey). The house has plaster façade and the maintenance costs include cleaning, repair of plaster, painting and scaffolding etc. Also, the costs for repair of the three degrees of damage in window, balcony door and roof connection are shown. Small,
medium and extended damages are defined in chapter 4.4. The costs are calculated for a wall area of 3 m x 2.5 m with one damage (window, door), and with only the costs of the wall materials, not windows, doors, etc.

Figure 6.6 indicates that repair cost of an extensive damage at a window will be relatively high compared to the building cost of the wall element, more than 50% of production cost. This is because of opening up a large part of the wall and floor/ceiling and drying during a long time. Repair costs are also generally higher than new construction cost because the work is not as effective. Figure 6.7 indicates that also a medium damage at the balcony door gives relatively high cost, because of opening a lot of the wall which is quite complicated behind the balcony.

![Figure 6.6](image1.png)

**Figure 6.6** Cost of damages at window connection in structural frame wall according to chapter 4.4.2 compared to cost of wall construction and regular maintenance.

![Figure 6.7](image2.png)

**Figure 6.7** Cost of damages at balcony connection in structural frame wall according to chapter 4.4.4 compared to cost of wall construction and regular maintenance.
Figure 6.8 Cost of damages at roof connection in structural frame wall according to chapter 4.4.5 compared to cost of wall construction and regular maintenance.

Figures 6.9-6.11 show LCC of structural frame wall for 50 years. The net present value is the normal measure used in an LCC analysis; although others are available. A stream of future costs is converted to a net present value. The expected real discount rate per annum is significant for the calculation of net-present values and is here chosen 4%. The probability of moisture damage is difficult to assess. It is also hard to estimate when a probable damage will occur and how long it takes before it is detected and repaired. It is both the size of a leak and the duration of leakage that affect how serious the damage will be. LCC have been calculated with the time to discover a small damage of 2 years, medium damage 5 years and extensive damage 9 years. Figures 6.9-6.11 show that LCC of improving the details with extra material (cost) is cheaper than having a risk of medium or extensive damage.

Figure 6.9. LCC of structural frame walls with damages at window connection according to chapter 4.4.2 and of wall with improved window detail with both steel profile and sealing tape according to figures 4.17 and 4.19, compared to LCC of wall construction including maintenance.
Figure 6.10. LCC of structural frame walls with damages at balcony connection according to chapter 4.4.4 and of wall with improved balcony detail with sealing tape according to figure 4.19, compared to LCC of wall construction including maintenance.

Figure 6.11. LCC of structural frame walls with damages at roof connection according to chapter 4.4.5 and of wall with improved roof detail with long eaves with panel according to figure 4.20, compared to LCC of wall construction including maintenance.

In figures 6.12-6.13 the costs of exterior wall with CLT structure and regular maintenance are presented (grey). The house has wooden façade and the maintenance costs include repainting and scaffolding etc. Also, the costs for repair of varying degrees of damage to windows and balcony doors are shown. Small, medium and extended damages are defined in chapter 4.4. The costs are calculated for a wall area of 3 m x 2.5 m with one damage (window, door), and with only the costs of the wall materials, not windows, doors, etc.
Figure 6.12 Cost of damages at window connection in CLT wall according to chapter 4.4.1 compared to cost of wall construction and regular maintenance.

Figure 6.13 Cost of damages at balcony connection in CLT wall according to chapter 4.4.3 compared to cost of wall construction and regular maintenance.

Figures 6.14-6.15 show LCC of CLT wall for 50 years. The net present values are calculated based on the same assumptions as for the structural frame walls. Figures 6.14-6.15 also show that LCC of improved details with extra material (cost) is cheaper than having a risk of medium or extensive damage.
Figure 6.14 LCC of CLT walls with damages at window connection according to chapter 4.4.1 and of wall with improved window detail with both steel profile and sealing tape according to figures 4.17 and 4.19, compared to LCC of wall construction including maintenance.

Figure 6.15 LCC of CLT walls with damages at balcony connection according to chapter 4.4.3 and of wall with improved balcony detail with sealing tape according to figure 4.19, compared to LCC of wall construction including maintenance.
7 Conclusions

The scenarios used in this study were based on experiences from builders, timber house producers, insurance companies and experts in timber building. The experiences of timber facades on low-rise buildings are extensive, while experiences of different types of damages vary because they do not occur that often. The scenarios contain many uncertainties due to design, execution, and exposure time and if the structure can dry between exposures. However, the use of scenarios makes it possible to evaluate the consequence of a damage caused by failure in a connection detail. Different improvements of detail connections to increase moisture safety were also evaluated regarding risk of damage, costs and environmental impact.

Connections at windows, balcony doors and roofs were identified as risk areas, and environmental impact assessments and life cycle costs were calculated for different damage scenarios. The results showed that even small and inexpensive improvements that will increase the moisture safety only have a small impact on the environment compared to damages over the building life time. The monetarization of consequences demonstrated the relevance of moisture safety measures to avoid high costs for timber building industry and house owners.
8 References


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