

# CONSIDERATION OF DISTURBANCES AND DEFICIENCIES IN THE MOISTURE SAFETY DESIGN OF TALL TIMBER FACADES

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**ABSTRACT:** In order to create high quality and durable wooden buildings, a close look at moisture exposure is necessary. Too often, the moisture design process considers only the plain wall without disturbances or deficiencies. This paper points out the necessity to take details and human errors into account as well. Moreover, it gathers current knowledge about deficiencies in standards and literature and compiles it in a critical way. Simulations and experiments with intended deficiencies are presented and discussed.

**KEYWORDS:** tall wooden facades, moisture safety design, deficiencies, human error

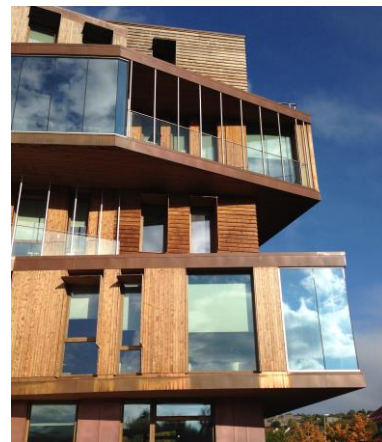
## 1 INTRODUCTION

Moisture is one of the most dangerous enemies of wooden structures: Mold at the interior surface is not aesthetic and leads to unhealthy indoor climate. Varying moisture conditions in wooden products result in dimensional changes like swelling and shrinkage and consequently in cracks. Increased heat losses have to be considered when the insulation gets too wet. Most dangerous is rotting within the wall: If decomposition of the load-bearing structure cannot be seen, it can spread unopposed and lead to unexpected collapse.

However, moisture safety is often a minor aspect in the design process what leads inevitably to many damages: a Norwegian study points out that 76 % of failures in their buildings can be associated with moisture problems [1]. Other countries might show comparable values. The mentioned study was mainly performed for low-rise buildings. It shows that it is not yet possible to get a grip on the problem of moisture even for small-scale structures.

But nowadays timber buildings are planned and built higher and higher and with this, difficulties within the whole life cycle will even increase: The critical construction process lasts much longer than for low-rise buildings and therefore, poorly protected components are longer exposed to rain before they are sealed beneath a water-tight layer. In contrast to a common single-family-house which consists usually of just four walls and a roof, multi-story timber buildings are often prestige projects with complex facades and a lot of details (see Figure 1). This complexity leads to a higher risk of making a mistake. Moreover, this mistake could be repeated many times because the number of identical details grows with

the building height. During its life time, a high building is exposed to higher wind loads and consequently to more intense wind-driven rain exposure. Last but not least, maintenance and repair throughout the life cycle is much more difficult and expensive for taller structures.



*Figure 1: NINA-building in Trondheim, Norway*

Since the danger of moisture was underestimated in the past, more knowledge about this topic is required. Essential is thereby to look behind the plain and “perfect” facade set-up. This paper outlines the importance of considering details, human errors and other deficiencies. It shows how powerful nowadays simulation software already is, but it deals also critically with the actual design process, the state of standardization, and the lack of information about moisture penetration due to deficiencies. In order to fill the gap of missing knowledge, a set of experiments is described in chapter 4.

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## 2 STATE OF THE ART

Good news first: In standards, research and state of the art literature much knowledge is already available how to create a moisture-safe building: water-tightness, airtightness, a constrained initial moisture content of wooden components, sufficient air change rates and drainage for ventilated claddings, flashings, distance to horizontal surfaces, and wood protection by means of construction are just some of the keywords which should be considered in every design process. The knowledge how to create a perfect moisture-safe building does exist.

But how does it come that there are so many moisture-related damages? Because the world is not plain and perfect and clients are looking for individual appearance of their buildings.

### 2.1 THE WAY FROM A PLAIN WALL TOWARDS DETAILS

In everyday life, usually an undisturbed plain wall is used for verifying the moisture safety of a building. Approaches like the Glaser method which is included in the German standard DIN 4108-3 [2] and the European standard EN ISO 13788 [3] are only valid to investigate static conditions of an undisturbed wall section. Even if dynamic processes are considered and Heat, Air and Moisture models (HAM) are used, many engineers neglect 2-dimensional processes and the possibilities to consider imperfections.

Examining the plain wall is the inevitable starting point for the design process. But literature, experiments, HAM simulations and common experience show more and more, that this is not the decisive point of interest if it comes to moisture problems. R  ther examines in [4] wall sections with different kind of ventilated, small-sized claddings. Even the large open gaps in a shingle cladding which serves as 1<sup>st</sup> exterior defense layer do not lead to an appreciable amount of water in the core of the structure – as long as the second defense layer of the wall remains intact (cf. Figure 2).

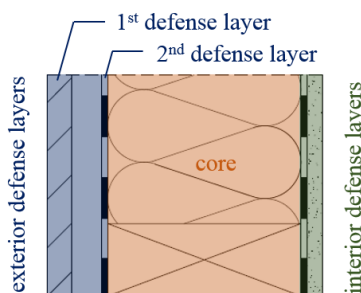


Figure 2: Defense layers of a ventilated composition

However, to make a house functioning, details like windows, corners, and projections must disturb the plain wall (see Figure 3). And with these disturbances, the risk of imperfections and deficiencies increases rapidly.

Deficiencies can have many causes. In all stages of the building, human error could occur from bad planning, transport damages and poor workmanship up to

insufficient maintenance. But even if all people in charge try to work perfectly, there are still some unavoidable phenomena like aging, movements of the building, uncertainties in material parameters or the systematic penetration of a membrane with fasteners which could lead to holes and water penetration.

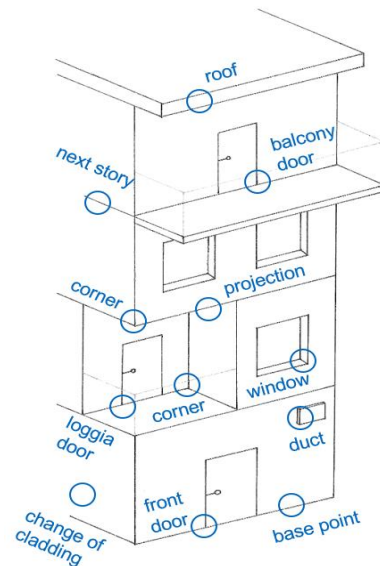


Figure 3: Disturbances of the plain wall

Planning and installing the connection of many different layers can be difficult and prone to errors. A missing sealant at a duct or a poorly planned window sill are enough to provide a path for moisture to penetrate into the structure or to form a horizontal plane where run-off water can accumulate.

### 2.2 CONSIDERATION OF DISTURBANCES AND DEFICIENCIES

The previous paragraphs show that some water will always find its way into the interior parts of the wall – mainly through details like windows, balconies or the inclusion of floors. This does not lead automatically to a damage, as long as a sufficient dry-out capacity is guaranteed. The important questions are (1) how much water can penetrate into the structure and (2) can it dry out again during the summer. Both standards and literature give first recommendations how this issue could be taken into account.

#### 2.2.1 Deficiencies in Standards

The following standards deal already with deficiencies and demand a certain dry-out capacity. However, most of them consider just one phenomenon – a combined evaluation of several deficiencies cannot be found, yet.

EN ISO 13788 [3] is the developed version of the Glaser method. It claims that each structure must be able to deal with 1 kg/m<sup>2</sup> additional moisture which is put in the middle of a condensation-prone layer at the beginning of the calculation. Within a period of 10 years, the water should dry out without causing too much condensation at neighboring layers. However, the 10 years are not a tight

failure criterion but shall just be used as an assessment tool and for comparison of various compositions.

**DIN 4108-3** [2] and the French standard **DTU 31.2** [5] determine the ratio of exterior to interior  $s_d$ -value to 1:10 and 1:5, respectively. This shall ensure that moisture is not captured within the wall but has the possibility to diffuse to the outside.

Depending on the air tightness of the building and small leakages in the air barrier, condensation due to convection might occur. **DIN 68800-2** [6] gives instructions for both Glaser method and HAM simulation: If Glaser according to DIN 4108-3 is used, a so-called drying-reserve of 100 g/(m<sup>2</sup>a) shall be proofed for walls. Using HAM software, a moisture source dependent on the class of air-tightness shall be implemented. Such an “Air Infiltration Model” is available in the software WUFI® and is used and evaluated below.

The American standard **ASHRAE 160** [7] is the only one known to the authors dealing with moisture penetration due to wind-driven rain (WDR): It shall be considered that 1 % of the WDR amount which hits the wall can find its way behind the exterior surface. Unfortunately, ASHRAE does not differ between ventilated and non-ventilated claddings. Simulations in chapter 3 show that the 1%-value should be reconsidered especially for ventilated claddings with two defense layers.

This list shows that there are several recommendations how deficiencies could be considered in the design process. But a closer look reveals that even those rules have their tricky parts when it comes to practical application: One challenge is to put the already available knowledge into the design process, especially in HAM software. Chapter 3 deals with this issue in detail. Another challenge is to find and enhance appropriate input parameters for models and simulation tools. Uncertain parameters could e.g. be the used climate file, the amount of a moisture source, or the initial moisture content of the components. For defining those input data more accurate, experiments could play an important rule (see chapters 2.2.2 and 4).

### 2.2.2 Deficiencies in Literature (Experiments)

Looking into literature, several researchers try to get more information about the question how much water penetrates into the wall when there is a little hole. The following paragraphs give a selected overview of some promising approaches.

Fox investigates in [8] a test hut in Waterloo. High thermal resistance timber frame walls are exposed to real weather conditions. Additionally, air is injected into the assembly in order to simulate an air leakage. The evaluated moisture content of the OSB sheathing increases significantly for the period of the air injection. However, an additional exterior insulation layer helps to reduce the risk of mold growth.

Another field investigation is described by Smegal in [9] and [10]. The performance of seven different wall panels is evaluated with respect to relative humidity, temperature

and wood moisture content. In addition to the natural weather of Vancouver, the panels must withstand some extra water which is put on the interior and exterior surface of the sheathing. The artificial wetting phenomena lead to a clear increase of the moisture content within the walls, but no mold or decay is found when they are deconstructed.

A different approach is carried out by Sahal [11]. Not additional air or water is introduced, but intended deficiencies clear the path for water to penetrate into the structure. A window, an electrical outlet and a duct disturb the plain wall of the test assembly. At their interfaces, where they are connected to the wall, pieces of sealant are missing and holes are made on purpose. The walls are exposed to a water spray lab test with static pressure difference. A collection trough behind the sheathing gathers and measures the amount of water which finds its way through the hole. With those results, a water entry function depending on the spray rate is developed.

Bossche [12] reduces the test set-up to a minimum. A water spray test with air pressure difference is performed on two polycarbonate plates. Both plates are perforated with holes in different sizes. The holes in the exterior plate shall simulate deficiencies in the first and second defense layer. With the holes in the interior plate, different degrees of air leakage can be represented. Behind the exterior plate, a collection trough is located which measures the amount of penetration water. This test set-up reveals very interesting information about the consequences of an air leakage: defects in the air barrier do not only lead to the well-known condensation effect, but they have also a major influence on the pressure conditions within the wall. If both second defense layer and air barrier are damaged simultaneously, water could be pressed through the holes and the effect of penetration increases many times over. These results underline the importance of considering not only one defect at a time, but to have a closer look on combined phenomena.

A series of experiments is described by Teasdale [13, 14]. In a first step, a wall-window-connection with intended holes between frame and sill is exposed to a water spray lab test for investigating how much water could reach the stud cavity in case of deficiencies. In the second part, the reaction of the components in the cavity due to water penetration is evaluated. Almost the whole water accumulates in the bottom plate whereas the upper parts of the wall (where the water is injected) dry out quite fast. This leads to the third part of the experiment: A pre-wetted bottom plate is inserted into different wall assemblies and the dry-out behavior is evaluated. The aim of the project was to find a repeatable and clearly defined method to simulate the effects of wind-driven rain and deficiencies in a lab test. This is a valuable approach since both WDR amount and deficiencies are very hard to grab in a usual lab test.

Experiments are one way to increase the knowledge about moisture processes. The previous paragraphs show that several people already started with investigating unintended moisture fluxes in various test set-ups. A second way to have a closer look at the reaction of the

structure can be found in hygrothermal simulations. Both ways complement each other: Experimental results are essential input parameters for HAM simulation, and vice versa simulations can help to work out newly required test set-ups. A big advantage of the computational approach is that several phenomena can be evaluated systematically with less financial effort and less expenditure of time than in experiments.

This advantage is exploited in the following chapter. A set of different moisture penetration phenomena is chosen and evaluated with WUFI® regarding the following questions:

- What is a reasonable order of magnitude for input parameters of moisture sources or the like?
- Which deficiencies have a major influence, and are there negligible ones, in other words how sensitive is the composition?
- How much resistance does the composition have against moisture penetration?
- How does the implementation of deficiencies into WUFI work? Are there any troubles when they shall be simulated or is it possible to consider each moisture penetration phenomenon easily?

Those questions will be answered in a mixture of literature review and own simulation results in chapter 3.

### 3 HYGROTHERMAL SIMULATION

In total eight different moisture phenomena are collected. Holes in various membranes, increased initial moisture content, run-off problems and aging are investigated separately and in combination. This selection shall reflect a wide choice of unintended moisture phenomena as they occur in reality. Exemplary simulations with the timber frame composition shown in Figure 4 are performed and evaluated in order to show the effect of each phenomenon.

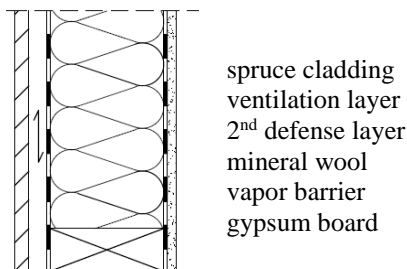


Figure 4: Timber frame cross-section

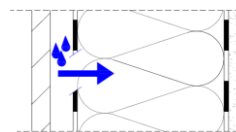
Those simulation results are depicted in unified diagrams with the following structure: The calculation time is 3 years and starts in October. The y-axis shows the weekly mean of the absolute water content of the insulation. Since the whole insulation layer is quite thick and conditions change a lot within this layer, only 2 cm at the exterior side are evaluated in the diagrams. This is the coldest and therefore most critical part when it comes to condensation. This leads sometimes to quite high water contents in the following evaluation. Looking at the mean of the whole insulation layer would result in more moderate values and perhaps underestimate the risk.

As climate input parameters the files of Holzkirchen, Germany and Oslo, Norway are used. In Holzkirchen the weather is quite cold and wet, whereas Oslo has a more moderate but nonetheless cool Northern climate.

The basic background of deficiency consideration is similar in 1-dimensional and 2-dimensional simulations. In order to reduce complexity, the explanations start with 1D simulations. In the second part, an exemplary 2D application is shown.

#### 3.1 ONE-DIMENSIONAL SIMULATIONS

In the following paragraphs each phenomenon is described one by one and evaluated with respect to difficulties in the implementation, choice of input parameters and reaction of the exemplary structure.



(1) HOLE IN THE SECOND DEFENSE LAYER

The first deficiency to be evaluated is a hole in the 2<sup>nd</sup> defense layer (also called wind barrier or water shedding surface). It is the layer which shall drain all the water which is pressed through little holes in the cladding and protect thus the core of the composition.

For the case this layer fails, WUFI provides the possibility to place a moisture source behind the 2<sup>nd</sup> defense layer. Relating to ASHRAE 160 the amount of the source is a fraction of wind-driven rain and the default value is 1%. Künzel uses in [15] this approach for a composition with an Exterior Insulation Finishing System (EIFS) and gets quite satisfying results.

However, there are some difficulties when ventilated compositions like the one in Figure 3 are investigated. This is done for the climate of Oslo in Figure 5. The red line states the water content of the investigated insulation layer for an undisturbed composition. In a second calculation, a hole in the 2<sup>nd</sup> defense layer is simulated by placing a moisture source with 1 % of the WDR amount in the exterior part of the insulation. The results are depicted by the blue line. There is a clear increase in the water content, but the results are still in a reasonable range and the values fall quickly down to the original values.

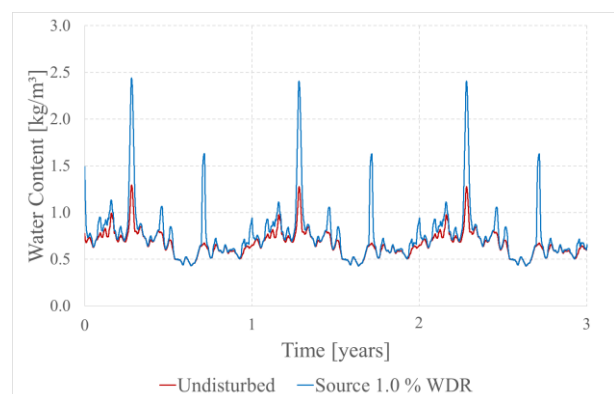
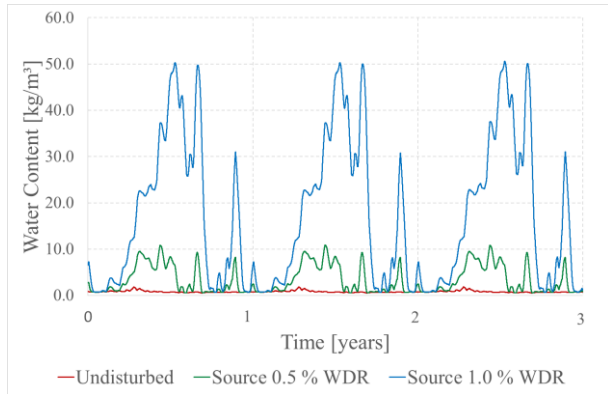


Figure 5: Moisture source WDR (Oslo)



This looks quite differently when the climate file of Holzkirchen is used (cf. Figure 6). The blue curve with the 1 % source reaches very high values and even if the amount of the source is halved and 0.5 % are used, the results are many times over the undisturbed case (green line).



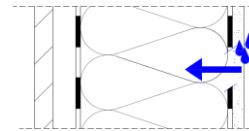
**Figure 6:** Moisture source WDR (Holzkirchen)

The combination of both figures shows a very high sensitivity of the set-up on the amount of wind-driven rain. For Holzkirchen even tens of percentage of the WDR amount decide about failure or no failure of the whole structure. For the Oslo climate file, this dependency is less pronounced because there is much less rain than in Holzkirchen.

This high sensitivity is very dangerous, because it is not possible to determine wind-driven rain that precisely [16]. The WDR amount can be defined by measurements, semi-empirical models or numerical simulation tools. But no matter which method is used, the values can differ from reality in the scale of 50 % or even more. Consequently, it is very hard to deal with structures which are very sensitive on a deviation of 0.5 % when the input parameter itself could vary about 50 %.

Furthermore, the amount of penetration water is not just dependent on the climate, but also on the composition itself. Lacasse describes in [17] that in ventilated walls ten times less water finds its way into the core of the structure than in non-ventilated assemblies. This can be deduced to the fact that a ventilated wall usually provides two defense layers which makes the composition less prone to failures compared to a non-ventilated wall with just one defense layer. Consequently, the amount of the moisture source should not be constant 1 % of WDR for all compositions, but shall be dependent on the kind of the structure.

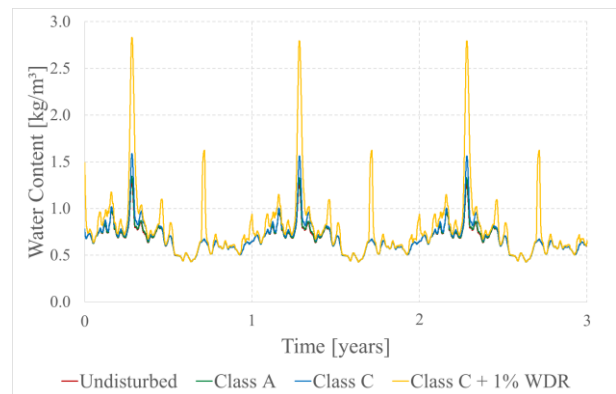
Relating a deficiency in the water shedding layer(s) to the amount of wind-driven rain is definitely reasonable and close to reality. However, the results should be treated with great care and more knowledge on the reaction of different compositions on WDR sources is necessary. This is why simulations and experiments described in this paper will be continued.



**(2) HOLE IN THE AIR BARRIER**

Comparable to a hole in an exterior membrane, a hole in the interior membrane serving as air barrier is thinkable. As mentioned in chapter 2.2.2, unintended air flow might have two consequences: Firstly, convection can bring humid warm air from the interior side into the structure; this air will cool down on its way through the insulation and condensation occurs as soon as the dew point is reached. The second aspect concerns the pressure difference from exterior and interior climate. An intact air barrier shall be the border between the two different pressures and prevent air from streaming through the wall.

For considering the first mentioned phenomenon – the condensation aspect – standards suggest an approach which is implemented in WUFI (see also chapter 2.2.1). Again, the problem is solved with the help of a moisture source. This time, the amount is dependent on the air tightness class of the building and the contiguous indoor air space. As location the suspected place of condensation shall be chosen. This will be the exterior part of the insulation next to the second defense layer for the current composition. The results of this approach are shown in Figure 7.

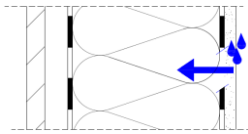


**Figure 7:** Moisture source air infiltration (Oslo)

The red line is again the undisturbed case. It is almost invisible below the green line which represents the results for a moisture source as it should be used in the best air tightness class A. The building can be classified in class A, when the air flow through the envelope  $q_{50}$  is lower than  $1.0 \text{ m}^3/\text{hm}^2$ . But even if the building is ranged in class C ( $q_{50} < 5.0 \text{ m}^3/\text{hm}^2$ ), the differences to the undisturbed case are of small importance (blue line).

Regarding the second protective function of an air layer – ensuring the pressure difference – a combined evaluation of holes in the 2<sup>nd</sup> defense layer and the air barrier is necessary. It is of course thinkable to add two moisture sources in WUFI, one dependent on WDR and the other one simulating the damaged air layer. And of course, their influences will overlap each other and result in a higher water content (cf. orange line in Figure 6). But WUFI adds just the amounts of both sources and does not consider the pressure differences. Remembering Bossche's expe-

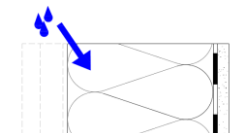
riments (s. chapter 2.2.2), the pressure aspect leads to an additional increase of the moisture content. Hence, the simulation results seem to underestimate the real moisture conditions.



**(3) HOLE IN THE VAPOR BARRIER**

The third functional barrier is the vapor barrier. For temperate climate it is located at the interior side of the composition and shall hinder the diffusion flux through the wall. It is possible to use the same membrane for both air and vapor barrier, as it is done in the current example.

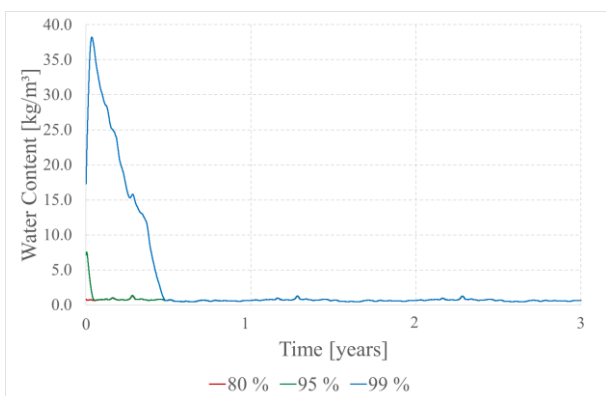
Using a moisture source might be possible again. However, not so much information can be found about the magnitude of the source. This might be due to the fact that much more moisture can be transported by unintended convection than by diffusion. And the previous figures and explanations show that even convection is not the most decisive factor. An additional moisture impact due to diffusion shall be kept in mind, but probably it is not the most important issue to focus on.



**(4) RAIN DURING CONSTRUCTION PROCESS**

The higher the building, the longer is the construction period. Consequently, the risk increases that a rain shower occurs when the building is in a critical phase – e.g. without exterior water shedding layers – and unprotected insulation or wooden components absorb lots of water. In the worst case, the water-tight exterior layers are installed the very moment when the core of the structure is completely soaked with water. To prevent complete failure for this case, the composition must provide a sufficient dry-out capacity.

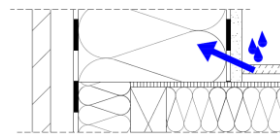
One possibility to consider this phenomenon in WUFI and to examine the dry-out behavior of the wall, is to increase the initial moisture content of all or of selected layers. In WUFI the default value for initial relative humidity is 80 % for the whole structure.



**Figure 8: Initial Moisture (Oslo)**

This is used for the red line in Figure 8 (only visible in the very beginning). Increasing the initial moisture to 95 % (green line) or 99 % (blue line), leads to a significant rise of the water content of the insulation. But the investigated composition has a very good dry-out capacity and all effects of the high initial moisture content are vanished within half a year. Note that this might not be self-evident for all kind of structures.

Adapting the initial moisture content is not the only possibility to take a rain shower into account in WUFI. Once more it is thinkable to work with a moisture source. This approach is described in [18]. Different kind of roofs are exposed to a moisture source which is 4 liter in the beginning and 0 afterwards. This leads to comparable dry-out lines as shown in Figure 8.

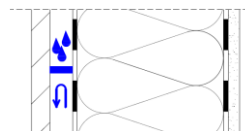


**(5) BUILDING MOISTURE FROM OTHER COMPONENTS**

A total different phenomenon – but with similar consequences – is the built-in moisture of the used materials. For instance, floors out of concrete and screed bring very much moisture into adjacent wall sections. Since this water is introduced into the structure at the beginning of its life-time and must dry out again, this situation is very similar as for the rain shower during the construction process – only the source of the additional moisture is another one.

Consequently, the implementation of this phenomenon in WUFI is quite similar as before. Either a moisture source can be used or the initial moisture content of all or of selected layers can be increased.

And there is another detail in simulation technique which considers this problem. All of the shown simulations start in October. This is suggested by the WUFI developers as the worst case scenario for the composition because the high initial moisture content meets the winter time with low dry-out possibilities. This means the structure is wet for a long time.

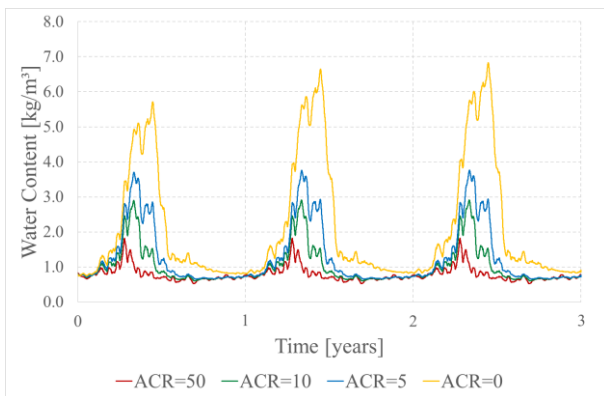


**(6) RESTRAINT OF VENTILATION AND DRAINAGE**

The air layer in a ventilated cladding has different tasks, e.g. providing a drainage space for the water which penetrates through the cladding or removing humid air by ventilation with the exterior air.

Regarding the air movement, WUFI works again with sources. A so-called air change source is a combined heat and moisture source. Located in the ventilation layer, it controls the interaction of exterior air and the conditions in the ventilation layer itself. Its amount can either be individual or a constant number of air changes per hour. Hauswirth suggests in [19] to use a constant air change rate (ACR) of at least 50 1/h for full ventilated claddings.

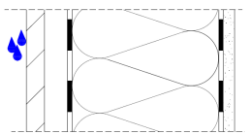
This is done for all previous simulations and once more depicted in the red line in Figure 9. Simulating that the air cannot flow unhindered in the ventilation layer by reducing the ACR to 10 1/h (green line) or 5 1/h (blue line), leads to a significant increase of the water content of the insulation layer. But it is still possible to dry out to “normal” conditions as they exist for sufficient ventilation. If there is no air change at all (ACR = 0), even the good dry-out capacity of the current example is not enough (orange line).



**Figure 9:** Air change source (Holzkirchen)

More difficult is to simulate the drainage (or more precise: a limitation of the drainage effect) in WUFI. As long as everything is perfect, all the fluid water runs down at the 2<sup>nd</sup> defense layer to the ground or to the next flashing. But as soon as there is a horizontal barrier (e.g. wrong installed battens or not-inclined flashings), the water can accumulate there and act as a very high exposure for adjacent wall sections.

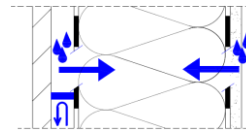
Known to the authors, there is no validated model or recommendation published which can deal with accumulated water in WUFI 1D or WUFI 2D.



### (7) ACCUMULATION OF RUN-OFF WATER

Fluid water running down at a certain layer is not only an issue in the drainage space. The main part of run-off water should actually occur at the exterior surface of the cladding. Again, this water does not cause any trouble as long as it can flow down at the undisturbed surface. But the same problems as in the drainage space can occur at the cladding when there is a horizontal plane where water can accumulate and stay there for a longer time.

This phenomenon is of even higher importance for multi-storey buildings because the amount of run-off water increases many times over. But as for the drainage space, it is very difficult to simulate this effect in WUFI.



### (8) AGING OF THE MATERIALS

The last phenomenon to be described here cannot really be categorized in the same order as the other seven. Aging is independent from human error and appears in various forms which can be deduced from several of the other phenomena: Aging makes membranes porous and less water- and air-tight. This could lead to holes and thus to all the consequences described in the first three examples. Movements of the whole building or swelling and shrinkage of wooden components can cause deformation and e.g. change the position of originally correctly installed flashings. This could disturb the paths for run-off water at the cladding and in the drainage space. It is very probable that several of those phenomena occur parallel due to aging. Therefore, it is very important to consider combined deficiencies as it is mentioned and explained in the previous paragraphs.

Talking about aging, maintenance comes into play. Since this is even more difficult and more expensive for higher buildings, it would be very useful to predict the extent of aging and its consequences. Therefore, the correct presentation of water penetration is essential. With the help of HAM simulation, an adaptable maintenance plan could then be applied which includes shorter intervals for areas where damages are predicted earlier and longer intervals for safer areas.

As discussed in chapter 2.1, the risk of damages is much higher for details like windows or the inclusion of floors. Since many two-dimensional effects can be found in the details, a look into WUFI 2D is advisable and is described in the following chapter.

## 3.2 TWO-DIMENSIONAL SIMULATIONS

Parallel to the simulations performed with WUFI 1D for a plain wall, 2-dimensional simulations are made to study the behavior of specific details (corner, balcony, window, roof ...). This chapter shows the results for the inclusion of a floor into the same timber frame wall as it is used for the 1-dimensional simulations in chapter 3.1 (see Figure 10 left side). The big advantage of 2D simulations for this example is that wooden studs and joists can be evaluated directly, and the 2-dimensional spread of moisture can be depicted.

From the above described moisture penetration phenomena, a hole in the second defense layer is selected. A linear moisture source with 1.0 % of the wind-driven rain amount is positioned just behind the exterior membrane. As boundary conditions the climate file of Oslo is chosen and the calculation time is again 3 years.

On the contrary to the 1D simulations, not the insulation is evaluated but the water content of the wooden components as they are numbered in Figure 10 (right side). This shows directly the reaction of the moisture-sensitive wood and is a good basis for further evaluation,

e.g. application of a mold model. The results for the climate of Oslo are shown in Figure 11.

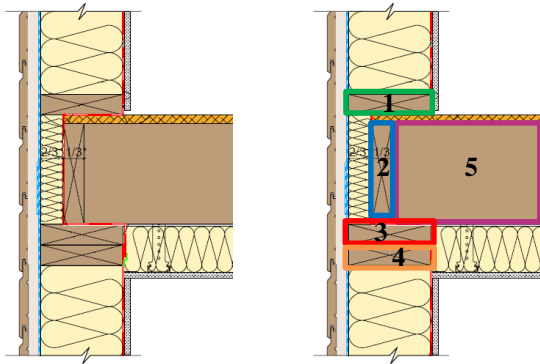


Figure 10: Cross-section inclusion of a floor

The joists of the walls and the floor itself show a decrease of the moisture content over time, describing the drying behavior of the connection. An exception is here the blue curve (2) which represents the results for the floor joist. This element has the largest exposed surface and consequently a higher water content. However, the results are still in a reasonable range and the values never exceed 20 % moisture content.

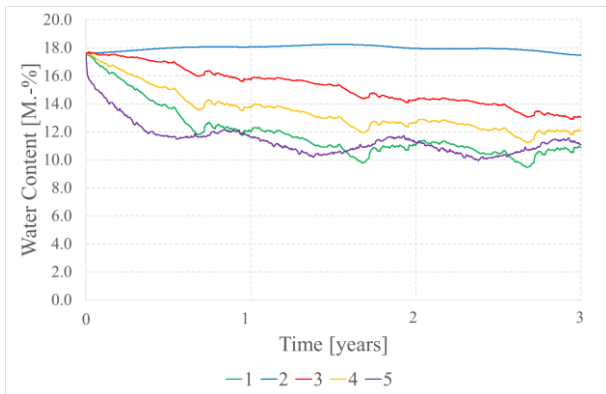


Figure 11: Inclusion of the floor - Oslo

In Figure 12 the same simulation is performed with the climate of Holzkirchen. The floor joist (2) and the floor itself (5) are not directly affected by the exterior climate and the related moisture source, so their water contents are comparable to those in Figure 11. But the wall joists (1, 3, 4) are not protected by an additional insulation layer and therefore more prone to the wetter Holzkirchen climate. Water contents go up to 25 % and steady-state conditions are not yet reached after 3 years. As for the 1D simulations, the composition is quite dependent on the climate files.

Later in the project, these results will be compared with other rates of WDR and with other details (inclusion of a balcony, corner, front door, window ...). The implementation of other moisture penetration phenomena like described in chapter 3.1 shall also be one of the next steps.

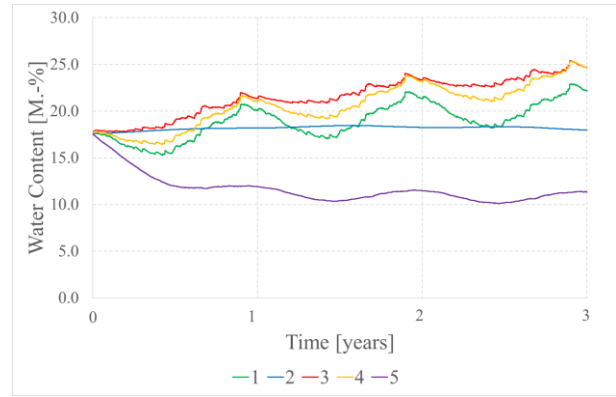


Figure 12: Inclusion of the floor - Holzkirchen

## 4 DEFICIENCY EXPERIMENTS

Two scenarios presenting moisture related problems which are frequently found in small and medium sized buildings and which are even more critical in high buildings will be studied in experiments: (1) the rain water uptake and storage in the building envelope during the construction phase before installing the outer defense layers (cladding and rain-barrier) and (2) disturbances which can happen due to construction mistakes, e.g. wrinkle of the rain barrier or due to design mistakes, e.g. wrong choice of the material.

These experiments will be carried out in a hot-box climate chamber. The technical specifications of hot-box experimentation are inspired by the standard ISO 8990 [20]. For the determination of thermal transmission properties in a guarded hot box, two samples can be tested simultaneously (Figure 13). The study will be carried out on a wall sample of 2 m tall by 0.69 m wide. The composition of the sample is similar to a standard timber frame plain wall (see Figure 4). The aim of the experiments is to characterize the influence of the implemented disturbances on the risk of damages (see below).

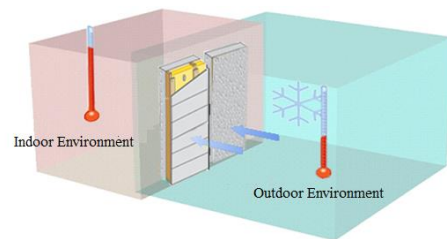


Figure 13: Hygrothermal test cells

Temperature, humidity and pressure regulation will be applied in each chamber to create differing steady state conditions.

The implementation of several sensors in the two wall samples will be done in order to assess the risk related to the strong presence of moisture (Figure 14): a sensor of thermal flow to measure the decrease of the R-value of the wall, temperature and humidity sensors located in the insulation material, and the use of a pin meter moisture to estimate the moisture content of the timber parts are installed.



In order to simulate the presence of unwanted water during the construction phase, the insulation will be sprayed before laying the cladding and the rain-barrier with different amount of water stages range from 1 liter to 5 liter. To simulate the risk related to design or construction mistake, several disturbances will be implemented in the defense layers (crack in the rain-barrier, missing vapor barrier...).

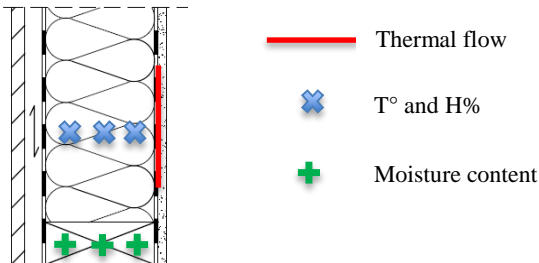


Figure 14: Implementation of the sensors

The experiments are currently in process and cannot be evaluated, yet. In the further scope of the project, the results of the experiments will be compared with WUFI simulations. It is also planned to work with details like the inclusion of a floor.

## 5 DISCUSSION AND FURTHER APPROACH

Several moisture penetration phenomena are evaluated in this paper. It is described how far they can be considered in the HAM software WUFI, which input parameters are necessary, how the composition reacts in general and which deficiency has major or minor influence on the results. Those outcomes shall be discussed here.

Regarding the input parameters, some recommendations can be found in literature and standards (cf. chapter 2.2). However, they should be treated with care. This is especially true for the amount of wind-driven rain which penetrates through small holes in the second defense layer. The following discrepancy can lead to very uncertain results: The exemplary used composition reacts very sensitive on changing climate conditions and changing WDR amount (cf. chapter 3.1). Even a modification of the moisture source amount in the magnitude of tens of percentage leads to completely different moisture contents in the structure. On the other hand, it is not nearly possible to forecast the WDR amount that precisely for the whole life time of the building. This discrepancy becomes even more evident when various kind of compositions need to be treated differently: For an EIFS composition with only one defense layer, the risk of water penetrating into the core of the structure is quite high and a fraction of 1% according to ASHRAE 160 might be appropriate. But ventilated claddings with two external defense layers are not so prone to errors and should be exposed to a lower moisture source in HAM simulations. But this means to be even more specific with the amount of WDR during the design process. To escape this problem of uncertain input parameters, results of further experiments like the ones described in chapter 4 are crucial.

The previous paragraph shows how important it is to have a look at the sensitivity of the composition on different deficiencies. The more sensitive the compositions react, the more accurate the input parameters must be chosen. From the investigated penetration phenomena, the moisture source dependent on WDR has by far the highest influence. Increasing the initial moisture content of all materials leads also to a very high reaction in the beginning of the simulation. But at least for the investigated composition it is possible to dry out quite fast. Changing the air-tightness class (and thereby simulating holes in the air barrier) does not have a major influence for the exemplary composition according to simulation results. But WUFI considers only the condensation aspect of the air flow and neglects the aspect of pressure difference which occurs when the second defense layer is damaged simultaneously and even more moisture could be forced into the structure. This leads automatically to the next issue of the current discussion chapter: the ability to implement the penetration phenomena into WUFI.

With the help of different moisture sources or the increase of the initial moisture content, many phenomena can be described in WUFI. Holes in various layers, rain during the construction process, building moisture from other materials, and restraint of the ventilation in the exterior air layer can be considered and evaluated. However, when it comes to complex combined phenomena, simulation results are not at the safe side or not achievable at all. This can be due to two reasons: Either the common knowledge about input parameters is not accurate enough, e.g. for wind-driven rain simulation, or the software code provides no model, e.g. for taking pressure differences into account. There is also no model available for considering a longer exposure time when run-off water accumulates at horizontal planes and stays there for a certain time. It could be thinkable to adapt the climate file and prolong each rain event, but this is a very theoretic approach and there is not yet enough knowledge about run-off available.

For reasons of comparability, this paper evaluates just one specific composition. In the further scope of the project it will be essential to extend this approach also to other assemblies. A sensitivity analysis for each composition should be conducted to see which parameter influences the results most. Only when the reaction of the composition to various climate files and deficiencies is known and the limit state for a certain exposure is defined, it is possible to compare them in an advanced way and to give recommendations for the practitioner which assembly shall be used in which climate conditions. That will lead to a semi-probabilistic approach for moisture safety design and is extended to a risk model for cost-efficient moisture-safe tall timber facades [21]. But this means that a lot of simulations are necessary as well as a well-structured way to evaluate them. Since it is very cumbersome to perform hundreds of simulations one by one, an automatized process using and evaluating WUFI 1D is described in a related WCTE 2016 paper [21]. Together with a set of selected 2D detail simulations as described in chapter 3.2, a sound knowledge about

moisture penetration processes in timber walls will be gathered.

## 6 CONCLUSION

Nowadays moisture design concepts deal often just with plain undisturbed wall sections. But the awareness rises that details like windows or ducts increase the risk for deficiencies and consequently the risk of additional water penetration. Very good tools are available in HAM-software like WUFI to consider holes in membranes e.g. the second defense layer. The software can also deal with an increased initial moisture content due to e.g. a rain shower during the design process. However, some combined phenomena like holes in both air barrier and second defense layer cannot be depicted correctly, and the selection of correct input parameters is not a straightforward task. The values given in literature and standards can often serve as a good reference point, but especially when it comes to consideration of wind-driven rain more research regarding input parameters is necessary. Moreover, common knowledge about run-off and WDR at high-rise buildings is quite low at the moment. Further simulations and experiments will gather more information about moisture penetration phenomena.

## ACKNOWLEDGMENTS

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Used software versions:

- WUFI 1D Pro 5.3.4 Moisture design tool for architects and engineers. *Fraunhofer Institut für Bauphysik*
- WUFI 2D Version 3.4.2. *Fraunhofer Institut für Bauphysik*