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## Hygrothermal Risk Analysis of Recently Constructed Timber Buildings Exposed to Outdoor Climate Changes by the End of the Century in Germany

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# Hygrothermal Risk Analysis of Recently Constructed Timber Buildings Exposed to Outdoor Climate Changes by the End of the Century in Germany

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**Abstract.** Scientific evidence predicts significant climate changes in the future and the world faces warmer days with extreme precipitation. The purpose of this study is to investigate the effect of predicted climate changes until 2100 on the hygrothermal behavior of well-insulated residential timber buildings are being constructed recently in Germany according to the new low and zero energy standards. Considering the facts that wood and timber constructions are sensitive to moisture and moisture changes and these buildings should have a service life of 50 to 100 years, the hygrothermal performance of several exterior wall assemblies has been analyzed by means of coupled heat and moisture transfer numerical model in this period. Predicted climate data -by the end of the century- for several cities in different Germany's hygrothermal regions, extracted from climate service centers' databases and applied as an outdoor condition. The article discusses the response of a number of buildings envelopes exposed to these exterior environments. Accordingly, critical aspects of moisture performance regarding the risk of mold growth and fungal decay were in each assembly analyzed. In this regard, relevant solutions were suggested aiming construction of more resilient timber structures to climate changes.

## 1. Introduction

Global warming is one of the certain climatic predictions, which has been confirmed by multiple scientific evidences. Observations from global and regional climate prediction models indicate similar transitions by the end of the 21st century in Germany; such as temperature increase, more humid winters, more heat waves and more heavy rainfalls [1]. These climate changes can lead to challenges affecting the construction industry; therefore, investigation on its consequences and finding systems that can adapt and/or resist to these effects are important issues.

Wood as an energy-efficient, environmentally friendly and renewable building material is being used more and more in the construction industry. However, wood is one of the most sensitive building materials to ambient conditions. With aid of a comprehensive coupled heat and moisture transfer method (HAM) have been presented by Künzle [2], and WUFI software generated based on that, the hygrothermal behavior of timber building envelopes under future predicted climate data will be investigated in this research. The main focus is on the moisture content of different layers of assembly especially wooden parts because their high moisture content leads to mold and decay growth which makes not only human health problems but also can degrade wood's mechanical properties. Christian Brischke, made many investigations on different types of fungi and decay may grow on wood species and particularly



based on different weather conditions in Germany, to develop a decay performance model [3]. European wood decay risk level map developed by H. Viitanen et al. [4–6] indicates durability and service life of wooden products according to current climatic conditions in Europe. In researches carried out by Finland research center (VTT), a mathematic-empirical model have been generated that can predict the possibility of mold growth in different building materials as a function of relative humidity, temperature, and duration the product exposed to these ambient situations [7]; the Mould-Index program developed by Fraunhofer- IBP (Institute of Building Physics) with cooperation of VTT have been used in this research for assessing mold growth probability in different part of assemblies.

Recent regulations in Europe are more restricted to the high energy performance of structures. Researches have been done by M. Lacasse et al. [8, 9], and many other authors indicate that high thermal resistancy of the envelope or better to say, usage of thicker insulation layer in structures, will decrease amount of heat flow in assembly and in case of moisture entrance into the envelope, rate of drying-out will become lower. Therefore, the risk of condensation and mold growth in these type of structure will increase and critical parameters should be investigated more precisely. One of the main effective parameters is boundary conditions, which is considered in this study. Effect of future climate changes in Germany applied as external boundary condition on some wooden structural envelopes to investigate their hygro-thermal behavior during their service life period.

## 2. Methodology

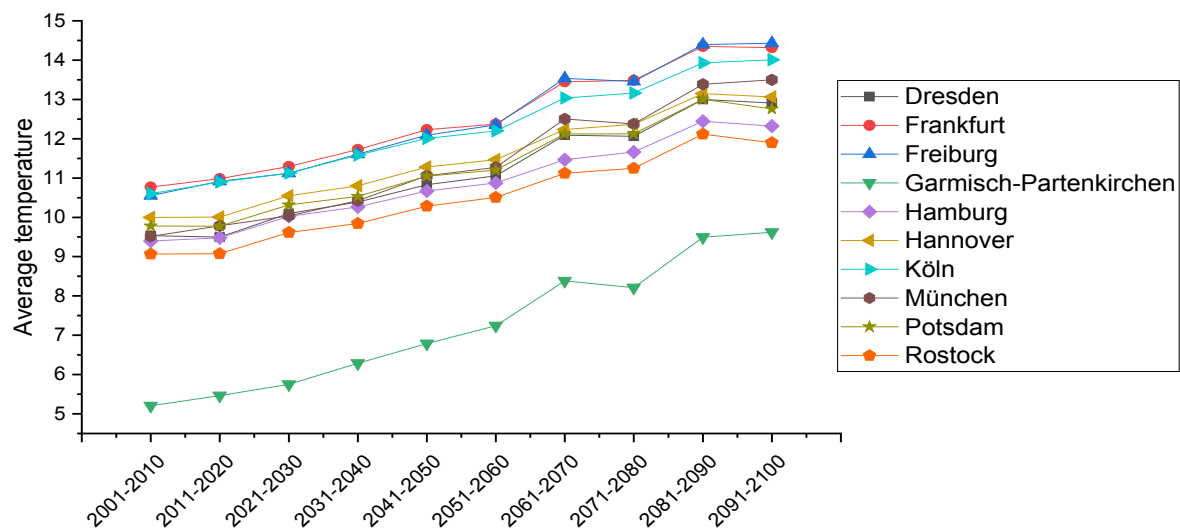
### 2.1. Climate data

Predicted climate data is calculated similar to numerical weather predictions but the forecasts are for a longer period. These data are available as regional and global data in different resolution and based on different scenarios for all over the world. Each predicted climate data is calculated based on a representative concentration pathway (RCP) which is defined based on the assumption of the amount of greenhouse gases are emitted in the years to come. RCP8.5 indicates the worst case when the business continue working as usual and RCP2.6 is related to the best situation based on climate protection conditions and the lowest possible greenhouse gas emission. In this research, since the focus is on Germany, REMO as a dynamic climate model is considered for investigating long-term climate transitions in the worst case situation (RCP 8.5) until the end of the year 2100. Ten cities in different hygrothermal regions of Germany (Rostock, Hamburg, Hannover, Potsdam, Cologne, Frankfurt, Dresden, Freiburg, Munich and Garmisch-Partenkirchen) considered being investigated more in detail.

Due to the fact that simulation of different assemblies under hourly changes of outdoor condition for 100 years with taking all climatic parameters into account, will produce huge files and their analyzing would be really time-consuming, in the first stage, it is decided to analyze assemblies under daily average outdoor temperature and relative humidity extracted from REMO data, to investigate the overall behavior of each assembly and the trend in behavior of each layer during the whole 21<sup>st</sup> century.

In the next step, for considering the effect of solar radiation and precipitation on the building envelopes, test reference year (TRY) climate data is used which contains hourly data of all climate characteristics needed for simulation. Mathematical and statistical approaches are used to calculate one year (TRY) climate data based on a combination of historical and predicted climate data with different RCPs. Temperature, relative humidity, short and long-wave sun radiation, wind speed and direction, and precipitation hourly data are extracted from TRY climate data, which is provided for a period between years 2030 to 2060 for all over Germany.

Interpretation of predicted climate data indicates that Frankfurt and Freiburg will be the warmest cities in Germany and Garmisch-Partenkirchen will be the coldest one, but the highest temperature increase during the whole century is related to Garmisch-Partenkirchen with approximately 4.5 degree Celsius increase in average decade's temperature. As it can be seen in figure 1, the diagram illustrates changes of average temperature in all cities except Garmisch-Partenkirchen are between Frankfurt and Rostock so, in the next parts, results will be shown under Frankfurt, Rostock and Garmisch-Partenkirchen climate data to avoid representing huge confusing data.



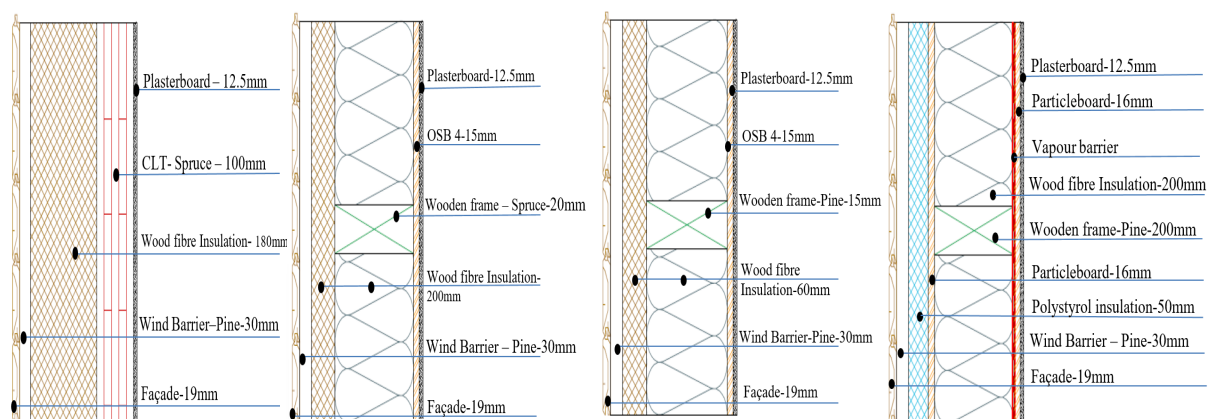
**Figure 1.** Average temperature changes by the end of the century in different cities in Germany

## 2.2. Wall assemblies

There are no fixed pre-described assemblies that can be defined for timber structures. Assemblies that can cover all requirements regarding the structural and hygro-thermal regulations can be constructed. In Germany, most of the building envelopes are open for moisture transport and the major focus is on energy efficiency and thermal insulation of buildings. Main structural systems in residential timber buildings include wooden frames, prefabricated wooden panels, and massive timber constructions.

In this research, one model from each of these structural systems have been investigated. Figure 2 indicates selected wall configurations. Plywood is considered as façade in all assemblies and all of them has a ventilated air layer with ventilation rate equal to 10 (1/h). Since wooden frame structures are the most common type of residential timber building, the effect of two different softwood (spruce-wall type 2 and pine-wall type 3) has been investigated just in this structural system. It should be mentioned that the phrase “structural elements” is being used in the text is related to CLT layer in wall type 1 and wooden frame in wall type 2, 3 and 4.

Material properties used in the calculation models were chosen from the WUFI material database. Following sketches indicate external wall assemblies that have been investigated in this research:



**Figure 2.** Wall types 1, 2, 3 and 4

## 2.3. Numerical simulation

Since the project is focused on the prediction of future climate effect for 100 years, there is no possibility for experimental tests, hence numerical simulation selected as the main tool. Many tools and software have

been generated for especially investigating the hygro-thermal behavior of building envelopes and all of them work based on coupled heat and moisture transfer in porous materials. WUFI® Pro is a finite volume based program which makes a comprehensive dynamic transient hygro-thermal analysis of structural assemblies with considering all climate characteristics as boundary condition. The predictions of the models in this software were in good agreement with the experimental tests data, which has been confirmed in various articles [10, 11], therefore this software with its Mould-Index add-on have been used to assess the risk of mold growth in wall assemblies when they were subjected to various climatic conditions.

Each assembly was analyzed under REMO daily mean temperature and relative humidity for hundred years in all cities. Since the possibility of condensation or mold growth starts from layers interface, benchmarks located on the surface of each layer in assemblies to be analyzed more in detail. Initial conditions for all layer in every assembly are same and equal to 20-degree temperature and 65% relative humidity. TRY hourly climate data is applied for analyzing the effect of solar radiation and precipitation, accordingly, same material properties for façade is considered for all assemblies with radiation absorptivity of 0.6 and rain fraction factor equal to 0.7. All walls are oriented to the south direction.

Indoor climate is defined with a sinusoidal curve with low amplitude with the temperature around 20 degree and relative humidity around 55 %. Since, a huge amount of result data produced in this project, average results for each decade in the wooden structural elements will be presented to make an overview of their moisture level over time.

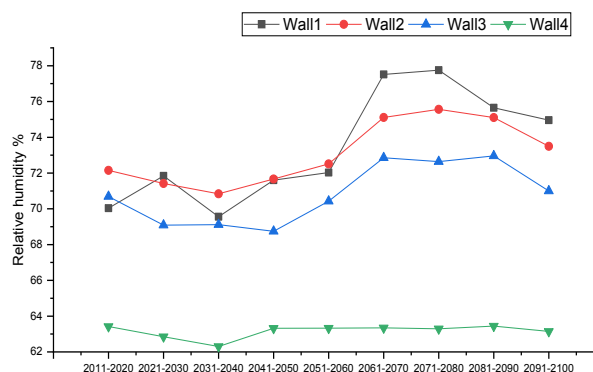
In the simulation, all layers has been considered as continuous plates as perfect condition. The issues such as gap between plates or human errors during construction or installation are out of scope of this work.

### 3. Results and discussions

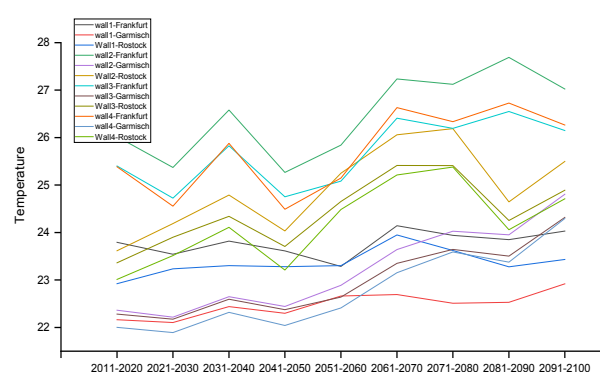
Following general hygrothermal performance can be seen the analyzed envelopes under hundred years' climate conditions.

- Amount of moisture content in wooden elements used as wind barrier will decrease in all assemblies and under all cities climatic conditions.
- The moisture content of structural elements will increase in all assemblies and under all cities climatic conditions.
- Amount of moisture content in the wooden frames made out of Pine is always in a higher level than the one made out of spruce; under all cities climate condition, this difference is around 5 %.

Onset, growth, and propagation of mold and rot in structures include limiting the temperature range, wood moisture content and time of exposure to suitable conditions. For evaluating the mold growth risk in assemblies, changes of relative humidity and temperature on the surface of each layer of assembly have been surveyed.



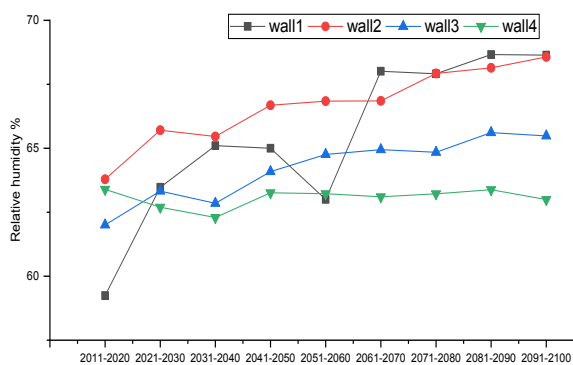
**Figure 3.** Maximum relative humidity on the outer surface of all structural elements in summer – under Frankfurt climate data



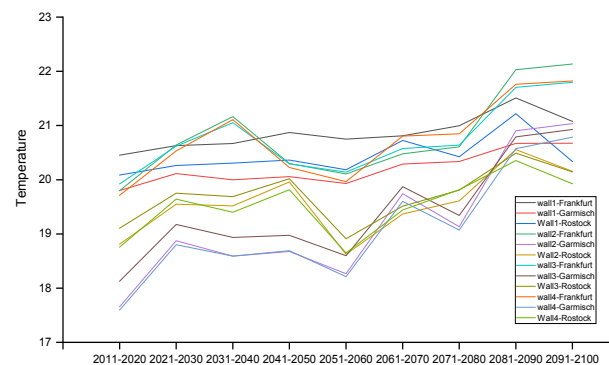
**Figure 4.** Maximum temperature on the outer surface of all structural elements in summer

The maximum amount of relative humidity will occur under Frankfurt outdoor climate data in all external wall assemblies. The diagram in figure 4 is related to the maximum temperature in outer surface of structural elements in all wall types and under the climate condition of all cities. This value during summer in all cities are higher than 22 degree which means if relative humidity exceeds 75 %, suitable condition for mold germinate is provided. Simulation results show the highest moisture content in all structural elements under Frankfurt climate condition and according to figure 3, wall types one and two are more prone to mold risk during summer. These walls analyzed with Mould-Index software to investigate the amount of mold growth rate based on the duration that assemblies exposed to critical condition.

In winter, although the temperature is higher than 20 degree on the outer surface of the structural elements in some of the assemblies but the amount of relative humidity even under Frankfurt climate is lower than critical values and there won't be any mold growth risk in this seasons (figures 5 and 6).



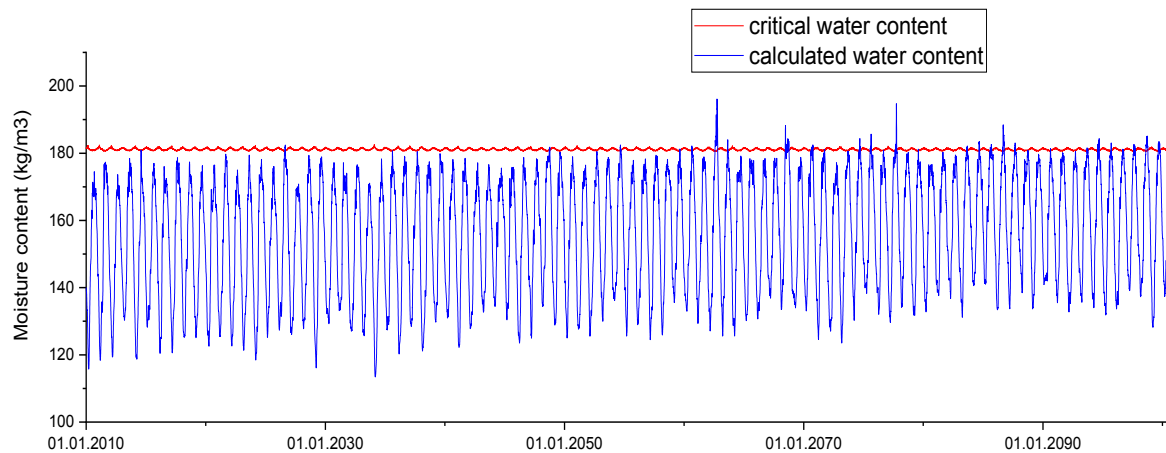
**Figure 5.** Maximum relative humidity on the outer surface of all structural elements in winter – under Frankfurt climate data



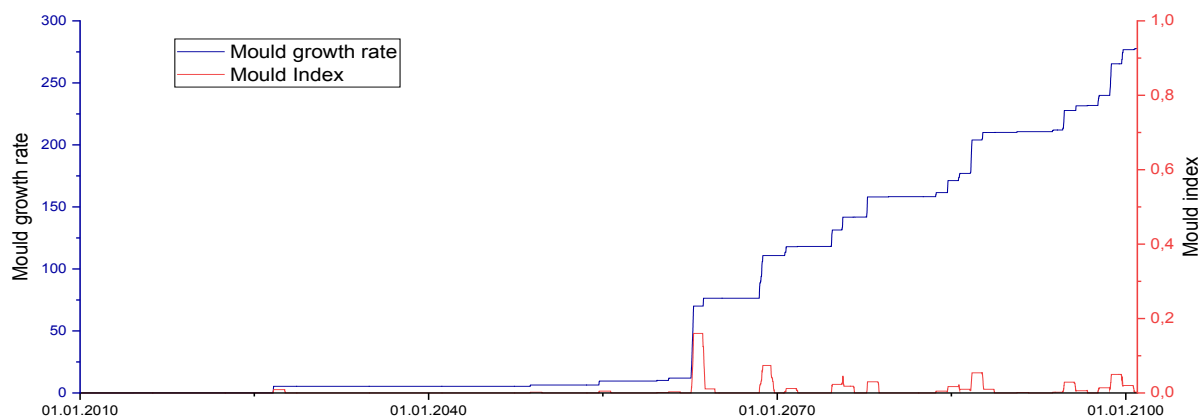
**Figure 6.** Maximum temperature on the outer surface of all structural elements in winter

Very low amount of mold germination appeared in the first and second wall assemblies under Frankfurt climate condition and the highest mold growth rate occurs in first wall type which has the thickest external insulation layer between the mentioned wall types. Mold-Index describing the mold-infested fraction of a surface in 6 levels from 0 which means there is no possibility for mold growth to 6 which means 100% tight coverage of the surface by mold. Simulation results in figure 8, show mold index on the surface of the structural element in wall type one, which is less than one, and it means mold growth in the interface of CLT and insulation layer will be in the microscopic level.

Figure 7 compares the amount of calculated moisture content on the surface of the structural element with its critical value. Maximum moisture contents in this layer happen in summers and in the second half of the century it will exceed the critical value when mold germination happen.



**Figure 7.** comparison of critical and calculated water content on the external surface of structural element – wall type 1 – under Frankfurt climate

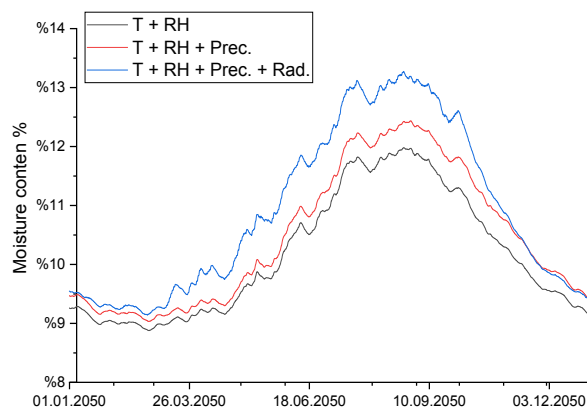


**Figure 8.** Amount of mold growth rate and mold index on the external surface of the structural element – wall type 1 – under Frankfurt climate

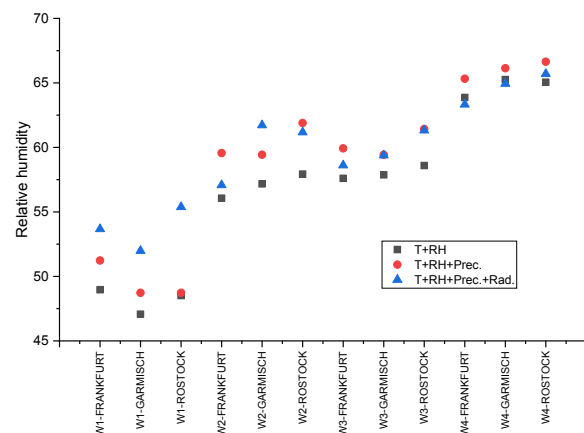
Mold growth rate indicated in Figure 8 is related to the situation that outdoor climate limited to just temperature and relative humidity. Effect of other parameters such as solar radiation and precipitation have been simulated under TRY climate data related to one year in the middle of the century (in 2050).

Figure 9 gives a close look to the effect of solar radiation and precipitation on CLT layer in wall type one under Frankfurt climate. It should be mentioned that CLT layer is supposed to be 5 layers made out of spruce and the moisture content in the diagram is related to the outer layer with a 2cm thickness, because of that the differences are not significant. Nevertheless, moisture content under the effect of both parameters are higher during the summer time and consequently, the amount of mold growth rate will become higher.

As shown in figures 10, both of these climatic characterizations will increase the amount of moisture content in structural elements. Wind speed and direction are also implemented in outdoor climate parameters to consider the effect of wind-driven rain into envelopes. The orientation of walls in the simulation are considered to be in the south direction, but regarding the changes of wind direction in different cities, in some cases, precipitation has a higher effect on increasing moisture content and in other cases combination of solar radiation and precipitation has more efficiency.



**Figure 9.** Compare effect of rain and sun radiation on the moisture content of structural layer of wall type 1 under Frankfurt climate



**Figure 10.** Compare average relative humidity on the surface of structural elements in all wall types and under climate of different cities

In comparison with the assemblies that analyzed under just outdoor temperature and relative humidity, average relative humidity of outer surface of structural elements will increase up to approximately 5%, by taking effect of solar radiation and rain into account.

Furthermore, there are other parameters which lead to underestimations in the amount of mold growth rate in these assemblies; for example, aging will decrease material functionality, hence building envelope after some decades won't work comprehensively like the time they were constructed, and all probable mistakes during construction are also ignored in this study.

#### 4. Conclusion

This project focus on the effect of future climate changes in Germany on the timber structures are built based on recent building physic regulations.

Results show that, in general, there won't be any significant moisture problem in residential timber building in Germany that may cause degradation in structural elements, but the west and south-western region are more prone to mold growth. In the first half of the 21st-century maximum probability of mold growth will be in the interface of wooden elements used as wind barrier with external insulation layer. This risk will decrease in the second half of the century with the reduction of moisture content in this part. However, in the second half of the century, the interface between structural element and insulation are in the higher risk of mold growth.

The solar radiation and driving rain load have an important influence on the magnitude of the moisture changes which leads to increase mold growth rate in the outer surface of structural elements.

On the other hand, prefabricated wooden panel structures show appropriate hygro-thermal behavior under the climate condition of all cities. Due to the usage of chipboard or OSB on both side of the structural element, there is a slight fluctuation of moisture content in the structural element within a safe border.

This project will be continued with sensitivity analysis to investigate the factors may increase mold risk in the mentioned assemblies.

#### Acknowledgments

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