Developing an event tree for probabilistic moisture risk analysis of urban tall timber buildings

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ABSTRACT:
Tall buildings are particularly exposed to high wind pressures combined with driving rain. Additionally, large-scale buildings require longer construction times in which the structural elements are especially exposed to moisture. Finally yet possibly important, inspection, maintenance, and repair possibilities are limited or costly in multi-storey envelopes. Against this background, large-scale timber buildings today must be innovative, flexible, highly insulated, but also moisture-safe, cost-efficient and durable.

KEYWORDS: urban buildings, moisture safety, event tree, probabilistic, risk analysis

1 INTRODUCTION

The interest in the use of wood, an almost carbon-neutral construction material, is growing not only for environmental reasons but also because of the health and safety criteria of industrialized produced and quality-assured design. Innovations such as the large-sized panels of stiff but still light-weighted cross-laminated timber, have been demonstrated in several multi-storey buildings, up on the high-rise building limit. These projects reaching for residential and commercial use show a large market potential for wood construction in the urban scale. The urban rediscovery of wood construction will develop in the medium term, but it has to be preserved against negative image resulting mainly from moisture induced damages in the long term.

2 BACKGROUND

With an increasing height of timber buildings the challenge is growing to provide moisture-safe conditions for the expected lifetime of building envelopes.
Compared to fire safety and static demands, the risk of failure due to moisture today is dramatically underestimated in planning, building processes, and in quality management. Although various statistics of construction damages clearly show the high amount of moisture related failure of the building shell resulting in an immense economic loss that is estimated to 3 – 5% of total annual investment in new buildings in Europe. Experts guess that this range may exceed in future due to higher insulated, more complex and enclosures that are more sensitive. Therefore 'semi-probabilistic safety concepts', similar to those in static calculations, are necessary to prevent negative consequences caused by inappropriate reaction of building envelopes to moisture exposure. There are basic and deterministic rules for the development of moisture safe facades as well as for the certain weak areas with geometry changes e.g. window openings and many others. This approach does not account for uncertainty, construction detail and variability of the climate exposure (CE) and the system reaction (SR) of a construction detail.
Development of a structured approach and risk analysis approach for moisture safety of construction details of building envelope as a probabilistic risk-façade-tool (RiFa-tool). The main objective is to facilitate the confident design of durable and therefore cost-effective design solutions for tall timber facades.

3 METHODS

3.1 FRAMEWORK

The risk model discussed here shall serve as a decision tool when it comes to the planning of details and connection points. Theoretically, WUFI® 2D, a two dimensional Finite Element Method (FEM) for hygrothermal calculation, could be used, and the same probabilistic approach as described for the plain walls could be applied for details alike. But this has two major problems: Firstly, a detail is much more complex than the plain facade and many different failures can occur. This means, it is not only important if e.g. the second defence layer is destroyed, but the exact location where it is destroyed is decisive, too. Comparing to the plain wall, this leads to a lot more cases that must be investigated. Secondly, a WUFI® 2D simulation takes hours whereas WUFI® Pro, the one dimensional simulation tool, for the plain wall runs within minutes. Both arguments show that using a first approach we call RiFa-Tool A, where "RiFa" stands for Risk-Façade (which requires hundreds of simulations) also for details, would lead to an unrealistic high time-effort in both preparation and calculation. The limit-state estimation is based on existing mould and

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decay models, namely [1], [2]. The moisture levels are derived from the simulation results and are scripted and computed within an open-source environment programmed in Python and also some MATLAB code for data analytics [3], [4].

There are other stochastic tools available to compare two details with each other and find the better solution. Based on the frequency of success and the frequency of failure of a specific detail that was often built in the past, decisions for future buildings can be made. The advantage of the alternative approach that we call “RiFa-Tool B” is the direct connection between the frequencies and the consequences of failure. This might lead to the realisation that using a diligent solution with higher initial costs could be cheaper than bearing the costs for extensive repair measures.

The user of RiFa-Tool B can choose between two ways of evaluating the risk of details, depending on how much information he or she has about the details. If the frequency of failure and potential repair costs are known (or can be guessed accurately enough) the so-called event tree can be used, that is described extensively in this paper. If this is not the case the so-called reversed approach can still find a threshold from which the user recommends one or the other solution. An expert can gather preliminary information regarding consequences. This estimate based on expert opinion fills the gap of missing quantitative information.

Event Tree Analysis (ETA) was developed because fault tree Analysis (FTA) went too complex to handle in certain specific environments e.g. nuclear power plant risk assessment [5]. The ETA is an inductive method to evaluate the consequences of a possible failure. Additional the ETA is a system analysis method hence related to system theory and engineering [5]. The process is applied by an initial event, which splits up the system in two reaction branches caused by the starting event. In the event tree analysis, an event that can occur in a system is considered as an initial event in the event tree and its possible effects on the overall system are examined **Fehler! Verweisquelle konnte nicht gefunden werden.**. In the event tree, the effects of the initial event on the system are graphically represented in the form of branches. In following steps, further events can be applied to the system and further branches are added.

Applied event tree methodology usually starts from the exploration of consequences, which set the frame for specific repair or replacement cost after a damage, and the initial cost for construction. By comparing two different connections, it brings up the difference in cost relative to each other and further which construction is prone to damage if a moisture safety expert compares both component joints with each other under identical surrounding conditions.

Table 1: F*açade moisture risk framework parts*

Identification of potential risk of our system building envelope or specific construction detail as <u>system components</u>
Description of barriers, protection layers and measures to reduce risk for <u>system description</u>
Determination of accidents (e.g. leakage) and <u>description of initiating events</u> (e.g. wrong planning, material, assembly, aging, …)
Limitation and selection of initiating events (high moisture) due to <u>system resistance</u> with potential damages
Analysis of moisture accidents and <u>system reaction</u> (e.g. conditions and damages under certain initiating events), formulation of event / failure trees (as probabilistic model)
Detection on input data (experts, experimentation, in probabilistic values)
Quantification of the prob. model
Evaluation of risk results, main causes of risks (identification <u>weak system parts</u>), possible risk reducing measures

Filling this event tree properly is the answer to the critical questions:

- “What can happen?”, and
- “How often does it happen?”

For the comprehensive risk analysis a third question is decisive:

- “What are the consequences?”

Consequences can be manifold, in the scope of the present project the emphasize lies on monetary costs. This is why branch 4 and branch 6 in *Figure 1* are especially important in the following analysis.

To completing the evaluation, the relevant costs must be collected. These are the initial costs on one hand and all the costs that occur in the case of a failure on the other hand. Next to the actual repair costs this might be costs for drying and cleaning, building up a scaffolding, or the loss of rent. With these values it is possible to calculate the risk of each detail. In stochastic, the risk R is defined as the product of the probability of failure Pr times the consequence C. This corresponds also to the expected value EV of the consequences. Since different risks may be summed up, the complete formula (1) is:

$$R = \sum_{i=1}^{n_E} \mathrm{Pr}(E_i) \cdot \mathrm{C}(E_i) \tag{1}$$

Where *R = risk*, *Pr = probability of an event*, *C = cost of an event* and *E = event*. This formula can be visualized in the following generic event tree, cf. Figure 1. For each system the expected value can be calculated by multiplying the values along each branch and adding up the branches in the end. This leads to an expected value for a system as follows:

$$EV_{sys} = P_s \cdot C_{initial} + P_f \cdot (C_{initial} + C_{repair}) \qquad (2)$$

Where EV_{sys} = *expected value of a system*, P_s = *probability of success*, C = *cost* , and P_f = *probability of success*.

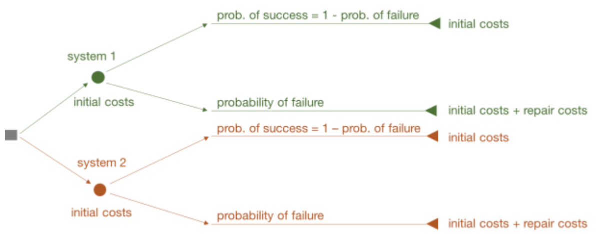


Figure 1: *Generic event tree for detail evaluation*

An equivalent equation can be found for a comparable system 2 but with different options maybe for materials and joint solutions implying also different costs. The system with the lower result shall be preferred, even if the initial costs might be higher, because money will be saved in the lifetime of the building.
The considered consequences do not necessarily have to be costs. Another unit might be thinkable, e.g. CO_2-equivalent when the sustainability is taken into account. This shows that the model is easily extendable.
The described approach works only when enough data is known about the probabilities of failure and about the consequences. But if e.g. a new system shall be analysed, and no experience values are available, a comparing analysis is still possible with the reversed approach mentioned above.

3.2 EXPERIMENTATION

For calibration of the event tree, a measurement protocol was development in order to compare the results of the experiment with the RiFa-Tool. The quantitative data gathered by these tests allow a better prediction of system behaviour and reaction to singular events. Each test scenario should be compared to a branch of the event tree that describes these scenarios to validate the developed decision-making process tool.

4 RESULTS

4.1 EVENT TREE PROCEDURE

The window, the balcony and the connection between roof and wall were selected for further investigation within the TallFacades project. The experts involved see these connections as most critical. On the example of a window the application of the event tree approach shall be shown in this paper. The first task is to identify critical risk areas as depicted by from the construction drawings, especially the cross-section. They show the locations where moisture ingress due to a deficiency is possible. The way of the water into the core of the structure and all the layers that could be damaged must be described for each failure event. In *Figure 2* and *Figure 3* the following scenarios should be considered:

1. The top board, which should actually shed the run-off water away from the window, could fail or be forgotten. This could lead to a water ingress behind the roller blind and – if the second defence layer (green) fails as well – to an increased moisture content in the wood fibre board and the load-bearing beam.
2. The drainage water running down at the impregnated wood fibre board must be shed away properly before it hits the horizontal plane of the roller blind. If this is not the case, similar problems as described in point 1 can happen.
3. The emphasize of the current project lies on exterior exposure, but in order to create a moisture-safe detail phenomena like condensation must be taken into account, too. It must be ensured that the air barrier is continuous. If this is not the case, the warm humid air from interior could cross the insulation layer, cool down and condensate in the core of the structure.
4. A very critical point is the exterior window sill and its flashing. Intruding water can cause large damages here.
5. The condensation mechanism in point 5 is the same as in point 3. Water ingress in position 5 might be a bit more dangerous since the water runs due to gravity even deeper into the structure. In case 3 it will leak at the top of the window and the damage will be detected quite soon.
6. The last location that is considered in *Figure 2* is the connection between the reveal panel and the window frame. The continuity of especially the second defence layer has to be ensured.

A risk analysis should be performed for each of these cases. Filling the event tree helps to remember all necessary steps and to keep the overview. The following chapter shows the application of the RiFa-B approach for the exterior flashing (number 4 in *Figure 2*).
An analysis of a balcony connection can be found in the following chapter. It shows the advantage of combining experiments with the theoretical approach of the event tree.
An attainment is the development and definition of a generalized technique for risk analysis of enclosure risk areas, cf. *Figure 4*. It supports the assessment of more complex, erratic events like human error or water intake by accidental damage. The procedure consists of five consequential steps starting with the exposure to moisture, followed by detail vulnerability description, moisture penetration processes and accumulation effects and closes with consequences. The risk analysis process utilizes the

paradigm of a moisture provoked event at a certain step as a branch in a decision tree methodology. Each test scenario is compared to a branch of the event tree that describes these scenarios to validate the decision-making process tool. Example showing how to use the tool in order to compare and optimize different solutions.

Vertical cross-section

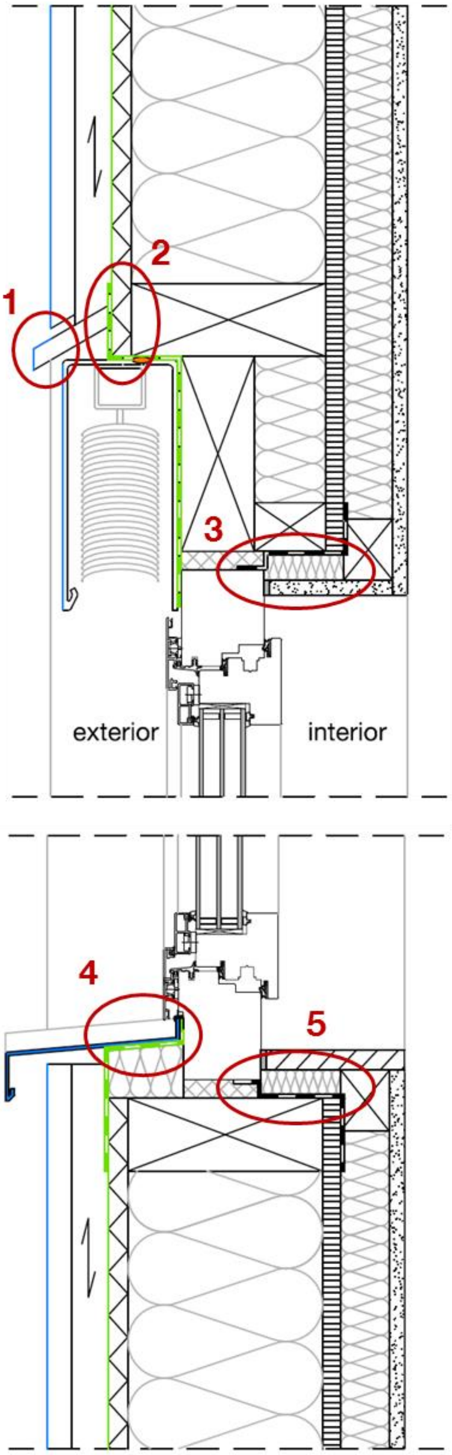


Figure 2: *Cross-section of a window detail in a highly- insulated exterior wall*

Horizontal cross-section

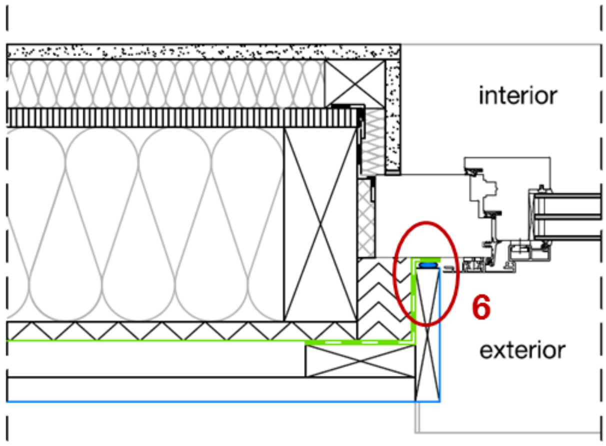
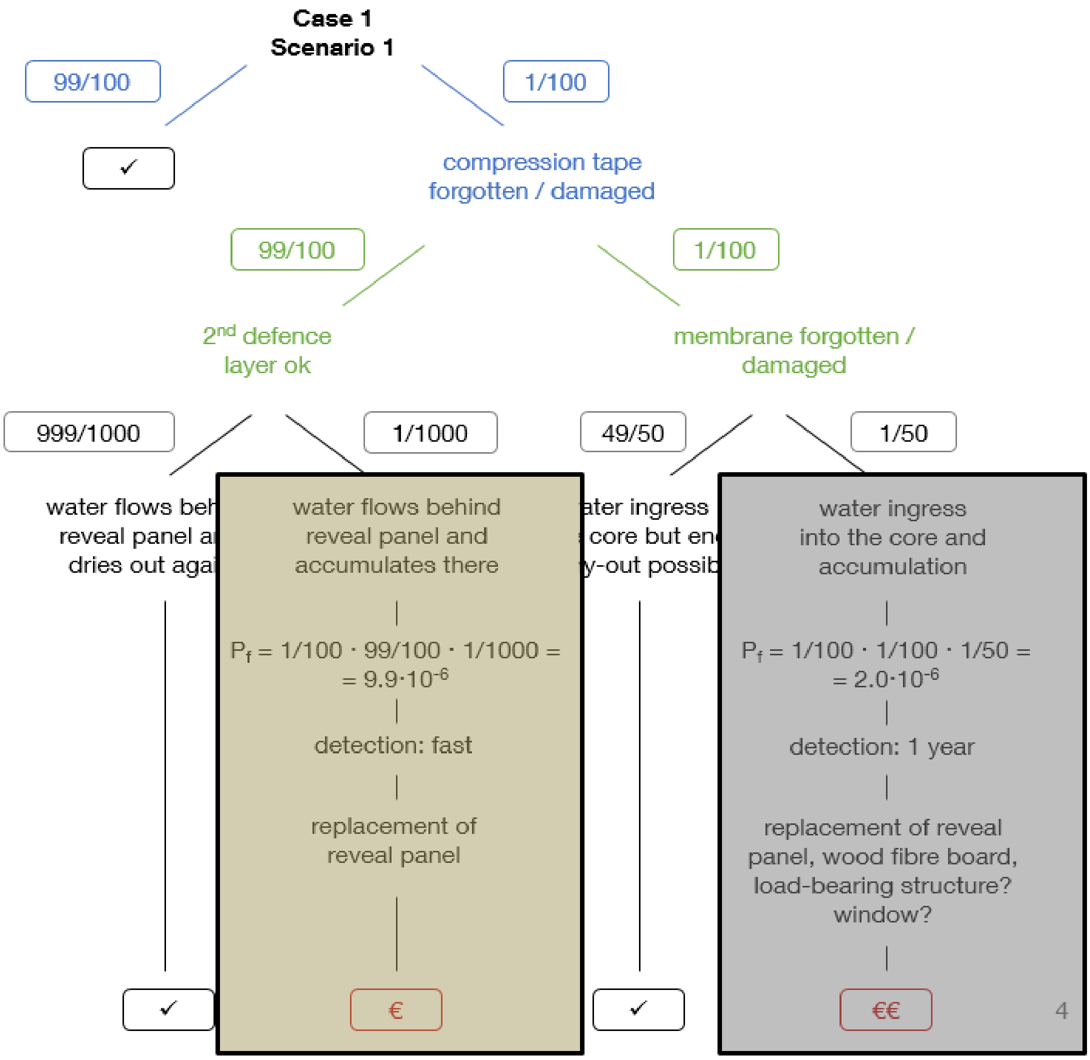


Figure 3: Horizontal cross-section of a façade joint, here a window detail



Case 1
Scenario 1
99/100
1/100
✓
compression tape forgotten / damaged
99/100
1/100
2nd defence layer ok
membrane forgotten / damaged
999/1000
1/1000
49/50
1/50
water flows beh
reveal panel a
dries out agai
water flows behind reveal panel and accumulates there
Pf = 1/100 · 99/100 · 1/1000 = = 9.9·10-6
detection: fast
replacement of reveal panel
€
ater ingress
core but en
y-out possib
✓
water ingress into the core and accumulation
Pf = 1/100 · 1/100 · 1/50 = = 2.0·10-6
detection: 1 year
replacement of reveal panel, wood fibre board, load-bearing structure? window?
€€
✓
4

Figure 4: *Exemplary event tree of a window – reveal construction detail*

4.2 PROTOCOL AND VALIDATION

The validation of the event tree procedure will be lead on the hygrothermal behaviour study of one singular point: wall-balcony connection. Samples (see *Figure 5*) are placed between two independent controlled environments (temperature and humidity regulation) and disturbances are applied on the samples (wet insulation material, cut in the sealing material…). Then the study of temperature and humidity profiles within the tested walls as well as specific moisture measurements of the various structural elements in wood allow to compare and validate the evaluation of risk given by the event tree.

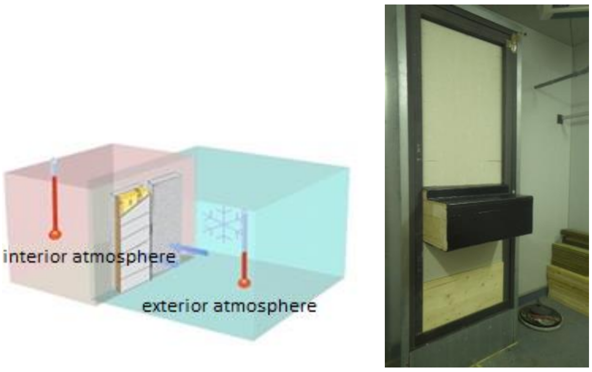


Figure 5: *Hygrothermal test cells and wall-balcony sample (exterior view)*

The samples were divided in 3 parts: top part, balcony and the low part. The samples were implemented with measuring sensors (temperature, relative humidity and water content in wooden elements), cf. *Figure 4*

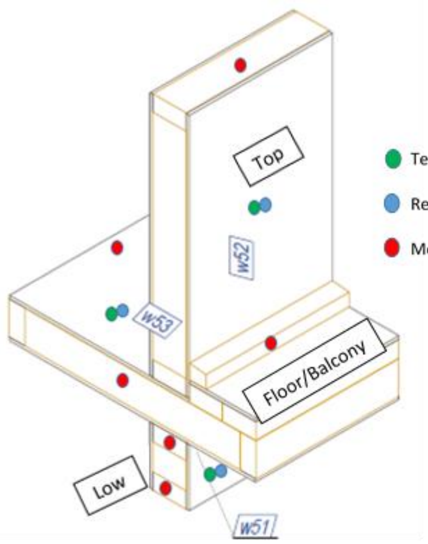


Figure 6*: Position of sensors*

The conditions of temperature and relative humidity of the atmospheres in the climatic chambers as follows:

T=23°C / HR=35% for the inside
T=3°C / HR=85% for the outside

The first objective of the tests was to assess the risk associated with the presence of disturbances that may occur on the several defence layers of the singular point:

- Wet insulation material (e.g. rain exposure during construction process)
- Cut in the sealing material (e.g. human mistake)

The second objective was to compare the results of the experiment with the event tree for the singular point wall-balcony.

Wet insulation material - Study of the effect of the rain during construction process and the dry-out behavior of the wall: Water spraying within the wall before the beginning of test.

Figure 7*: Wet wood fiber board (left), wet mineral wool (middle), spraying equipment (right)*

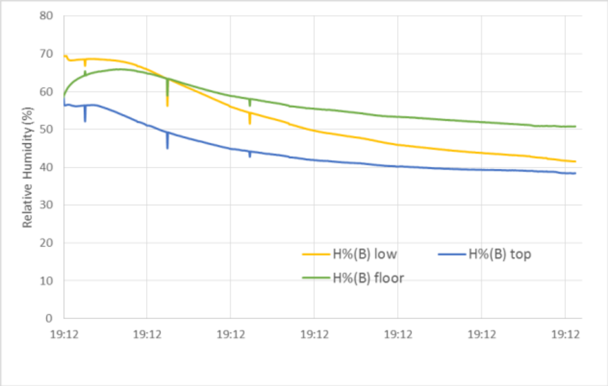


Figure 8: *Wood fiber relative humidity diagram showed dry-out behavior over a range of 7 days*

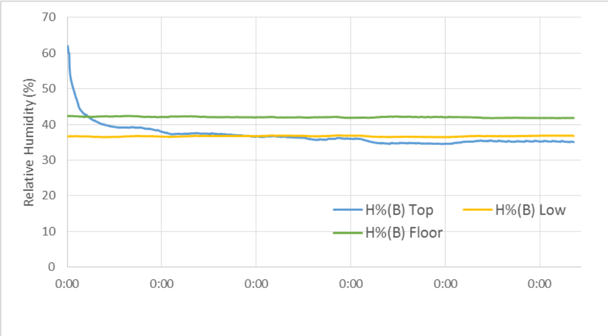


Figure 9: *Mineral wool relative humidity curve dropped immediately after spray test and remains constant over 7 days.*

The relative humidity curves shown a high drying capacity of the insulations materials: for the wood fiber, it takes 5 days to recover these relative humidity initial values and there is no impact on the temperatures. For the mineral wool, which is less hygroscopic, it only takes 12 hours to recover the initial relative humidity value.

Relation to Event Tree: The results of the experimentation confirms the capacity of drying out moisture of the envelope → No repair required, cf. *Figure 4*.

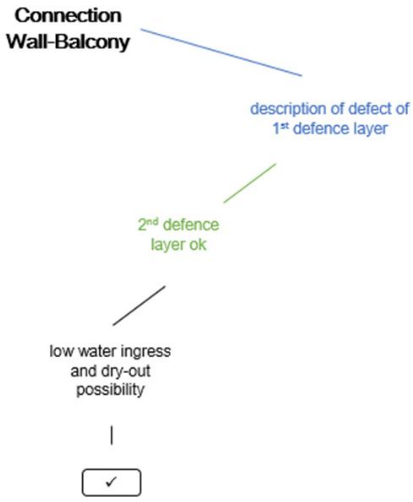


Figure 10: *Branch of event tree for the undamaged balcony*

Disturbance on the exterior side - Study of the increase of moisture during the life-time of the building: Hole or tear in the external layer + spraying "rain" on the sample.

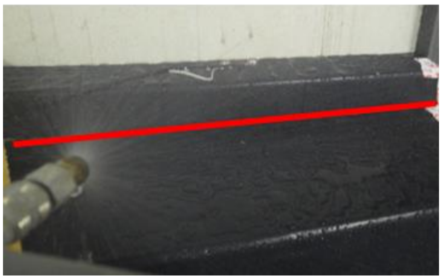


Figure 11: *Cut in the second defence layer and spray water on the cut*

A cutter was used to make a cut along the connection between the balcony and the facade (see red line), then the sample was watered using a nozzle connected to a pipe allowing a sufficient flow to simulate heavy rain.

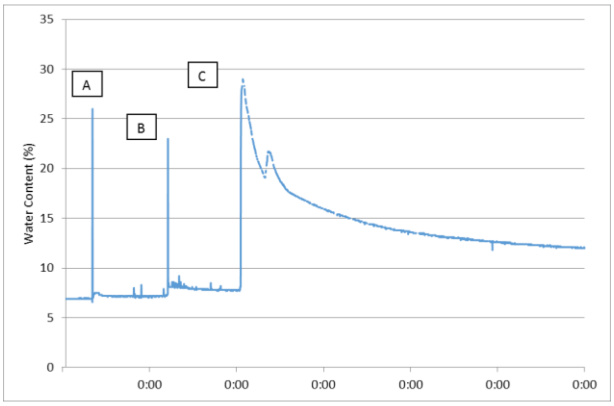


Figure 12: *Water content diagram showed spikes of three spray water actions in the wood structure of damaged balcony*
A: 1mm cut in the exterior sealing material + 10 minutes spraying (10 liters)
B: 2 mm cut in the exterior sealing material + 10 minutes spraying (10 liters)
C: 2 mm cut in the exterior sealing material + 20 minutes spraying (20 liters)

The moisture content curve shows that the wooden element close to the disturbance can displays high values and present a risk related to excessive humidity.

Relation to Event Tree: When the water content >2 0% there is a risk for the stability of the connection. The results of the experimentation confirms the risk of damage on the wooden element located close to the disturbance →Repair required and replacement of the balcony.

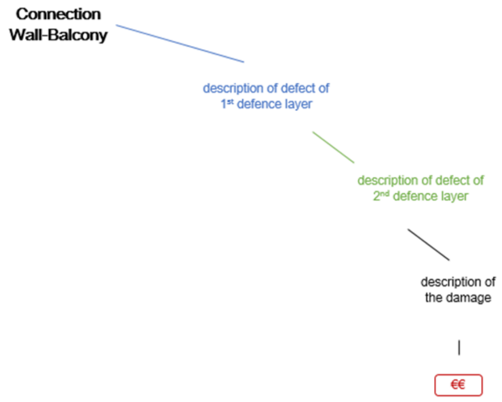


Figure 13: *Branch of the event tree for the "damaged" balcony joint scenario*

5 DISCUSSION

The straightforward achievement is the identification of damage scenarios related to human error and construction processes, which is closely related with the identification of building's architectural design and detail construction related risk areas.

Stakeholders are surveyed about facade related failure modes to gather a collection of statistical data that serves the project, to open industry's mind to a serious risk. Furthermore, the survey gives necessary input into event-tree models about human error influence and in which the feedback is an important source of structured data with systematic described specific cases and expert guess about event-based consequences.

1. Development of a risk model representation of exposure of exterior walls and facade detailing, considering moisture penetration and accumulation.
2. Categorization of risk areas of tall urban facades.
3. Implementation of various failure modes, e.g. mold and decay based on scientific literature.
4. Risk-Façade tool A (RiFa-Tool A) can be used for a versatile simulation process and to determine of indirect consequences in terms of repair or maintenance cost.
5. Derivation of a generalized procedure for risk assessment of envelope details based on an event tree methodology (RiFa-Tool B).
6. A second branch of the RiFa-Tool B is usable as a reverse consequence-based method to evaluate connections or joints of moisture risk areas.
7. Development of a measurement protocol in order to compare the results of the experiment with the RiFa tool B for the respective detail connection
8. Validation of the methods by the simulation of numerous façade constructions and their variants.
9. The monetarization of consequences demonstrated the relevance of moisture safety measures in order to avoid very high costs for timber construction companies.

It can be concluded that a risk-based approach for moisture-safe facade assessment was formulated. The

6 CONCLUSIONS

The event tree RiFa-Tool is usable as a reverse consequence-based method to evaluate connections or joints of moisture risk areas. The monetarization of consequences demonstrated the relevance of moisture safety measures in order to avoid very high costs for timber construction companies.

The event tree RiFa-Tool can be used for development of alternative joint solutions. The findings are relevant for construction companies due to the high monetary impact of possible moisture damages on envelopes of tall timber buildings.

The outlook can be summed up in the essential to formulate a semi-probabilistic design concept, embed risk-based approach in LCA-analysis, expand the RiFa-Tool on a numerical and hygrothermal simulation based tool for risk construction detail, and enhance the event tree RiFa-Tool with empirical data.

Additional to the presented event-tree approach there was also a numerical RiFa-Tool developed based on hygrothermal simulation with commercial software that allows the FEM computation of one-dimensional component cross-sections. The numerical RiFa-Tool is directly usable for prototype design, see the final research report of the TallFacades project.

Recommendation for the protection of wood against moisture-related damage, the current valid practice is to limit the allowable wood moisture content to u = 18-20% by mass. This boundary range is often found in national regulations within Europe and also overseas. It limits the permanent moisture content of timber. The limit already takes into account a safety margin, since the coniferous wood used in the building industry have moisture equilibrium of around 27% by mass and the growth conditions for wood-destroying fungi only start beyond this limit. This safety margin is very generous with a 50% surcharge. However it is reasonable that a variation of the moisture content over the inhomogeneous, natural material is also taken into account, as well as fluctuations in the moisture content due to usual, seasonal climatic conditions as simulations and test within the project have shown this as well.

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