Tall Timber Facades – Identification of Cost-effective and Resilient Envelopes for Wood Constructions (TallFacades)

FINAL REPORT

Title of the research project	**Tall Timber Facades – Identification of Cost-effective and Resilient Envelopes for Wood Constructions**
Coordinator of the project	Stephan Ott

BASIC PROJECT DATA

Project period	1.09.2014 – 30.06.2017
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URL of the project	http://www.tallfacades.eu

FUNDING

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<u>Germany</u> Agency for Renewable Resources (FNR)	476.800 €

<u>Norway</u>
The Research Council of Norway (RCN) 812.000 €

<u>Sweden</u>
Swedish Governmental Agency for Innovation Systems (VINNOVA) 343.707 €

Other public funding:

-

Other funding:

-

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DEGREES (if relevant)
Degrees earned or to be earned within this project.

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PROJECT SUMMARY REPORT

With an increasing height of timber buildings the challenge is growing to provide moisture-safe conditions for the expected lifetime of building envelopes. Tall buildings are particularly exposed to high wind pressures combined with driving rain. Additionally, large-scale buildings require longer times of construction in which the structural elements are especially exposed to moisture. Last but not least inspection, maintenance and repair possibilities are limited in high rise structures.

Compared to fire safety and static demands, the risk of failure due to moisture today is dramatically underestimated in planning and building processes and in quality management. Although 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 due to higher insulated, more complex and more sensitive enclosures in future. This may also lead to an image risk for timber buildings, if damages will increase in future. Therefore 'semi-probabilistic safety concepts', similar to those in static calculations, are necessary to prevent negative consequences caused by inappropriate reaction of construction to climate exposure. The main objective of the project is to facilitate the confident design of durable and therefore cost-effective design solutions for tall timber facades. The risk based RiFa-Tool taking into account exposure and vulnerability of façade systems will enable the moisture-safe design consistently.

Findings:

1. Development of a risk model representation of exposure of exterior walls and facade detailing, considering moisture penetration and accumulation.
2. Implementation of various failure modes, e.g. mold and decay based on scientific literature.
3. 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.
4. Derivation of a generalized procedure for risk assessment of envelope details based on an event tree methodology (RiFa-Tool B).
5. 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.
6. 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 RiFa-Tool A (numerical) is directly usable for prototype design, and the RiFa-Tool B (qualitative) 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 numerical RiFa-Tool A on critical connections and moisture risk areas, and enhance RiFa-Tool B with empirical data.

1.1 Introduction

1.1.1 Background

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 from damages in the long term. 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.

1.1.2 Objectives

The variety of configurations and variations of the building envelope and the diversity of the effects of the external and the internal climate necessitate assistance in the selection of material and design options. For this reason, based on risk analysis methods, a Risk Facade Tool (RiFa-Tool) will be developed which will enable planners and producers to make substantiated decisions for specific constructions. In addition, the tool is used to create a guideline for Tall Timber Facades - envelope constructions, which are developed together with industry partners for practical application.

The main objective of the project is to facilitate the confident design of durable and therefore cost-effective design solutions for tall timber facades. A risk based design tool taking into account exposure and vulnerability of façade components and systems consistently will enable moisture safe design. The risk based design concept for wooden facades is developed with relation to existing exposure models for wind driven rain coupled with heat and moisture (HAM) transport models and failure mode models. Moreover, a simplified semi-probabilistic design framework (comparable with the Eurocode 1990 load-resistance design format) is developed which enables easy utilization of the results of this project by practitioners. Based on the identified design concept standard best-practice solutions for durable façade systems and details (corners, windows, cornice, etc.) are acknowledged and documented within the project. Other requirements for constructions such as thermal transfer, load-bearing capacity, fire safety, sound transmission will be considered.

1.2 Results and discussion

Developments and Findings
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 in all partner countries are surveyed about facade related failure modes to gather a collection of statistical data which basically serves the project, to open industry's mind to a serious problem. Furthermore the survey interacts with an upcoming project step which models human error and in which the feedback is an important source of data with cases and expert guess based on them.
Findings:

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. The monetarization of consequences demonstrated the relevance of moisture safety measures in order to avoid very high costs for timber construction companies.

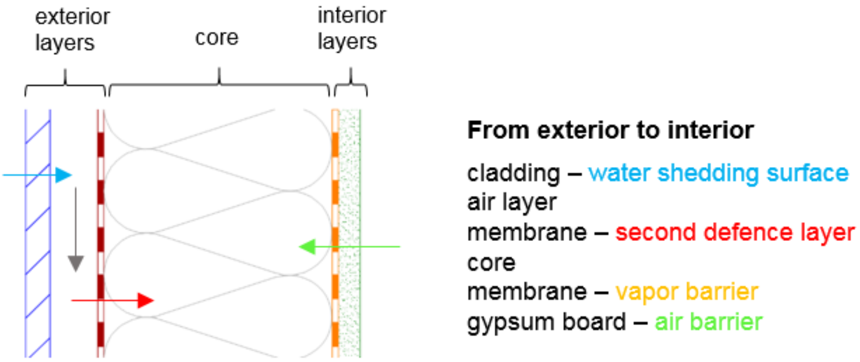

Figure 1. Barrier approach of a ventilated composition.

RiFa-Tools
Another important attainment is the development and definition of a generalized technique for risk analysis of enclosure risk areas, see Figure 1, Figure 4 and Figure 5. 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. It is called RiFa-Tool B, and is a qualitative methodology. It also comprises the development of a measurement protocol in order to compare the results of the experiment with the RiFa-Tool B for the singular point wall-balcony: each test scenario as shown in Figure 2 is compared to a branch of the event tree that describes these scenarios to validate the developed decision-making process tool.

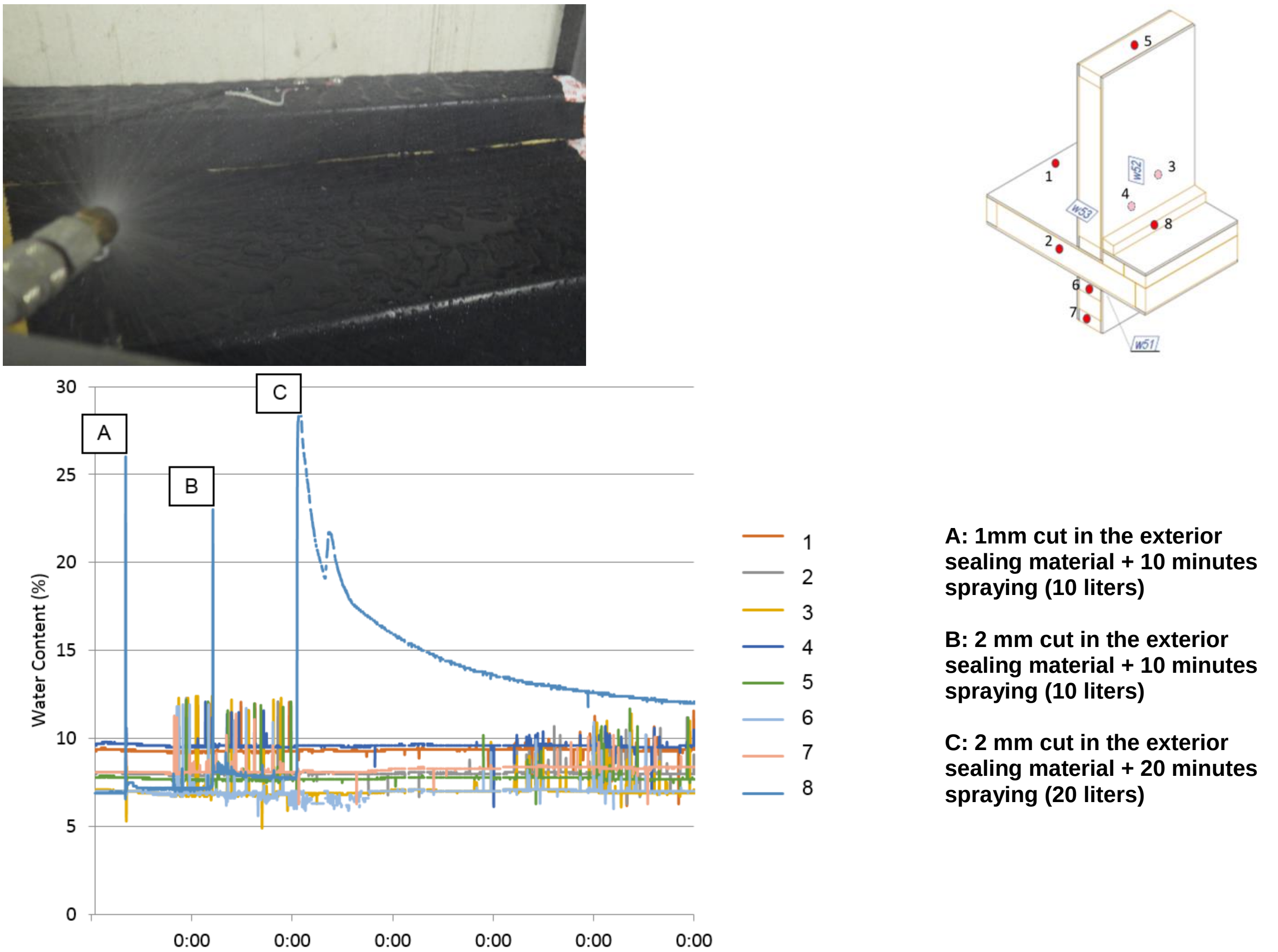

Figure 2. Spray test with damaged sealing of balcony, sensor positions of sample, test conditions A-B-C, water content monitoring (clockwise start upper left)

An important stage in development is the model representation of exposure of building enclosures, considering moisture penetration and accumulation as well as possible failure modes and consequences in RiFa-Tool A. For this tool, the model representation was translated into a tautly simulation process containing the facade design and the core hygrothermal simulation based on the existing and validated software package WUFI. The implementation of a parameterized climate data component that transforms continuous weather data from selected, project-related locations into probabilistic weather models was a necessary addition to core hygrothermal software. The reaction of the facade system simulated was analyzed over the period of 50 years, which is the reference from Eurocode technical building lifetime. Several failure modes were implemented based on traditional used moisture content limits but also quiet young ones from the latest developed wood failure models, see Figure 3. There is an appropriate quality of results, which are in line with what is observed for the examined facade components in reality. The facade compositions withstand moisture loads of the climatic region they are designed for. However, some compositions are behaving more robust to exceeding moisture content than others that makes them resilient and sustainable. The reason is a higher also quicker dry-out capacity of these compositions due to diffusion openness of exterior, second defense layers. It depends on the entire facade system what individual measures should be taken to improve them but often the change of paneling material with lower diffusion resistance will improve the entire system.

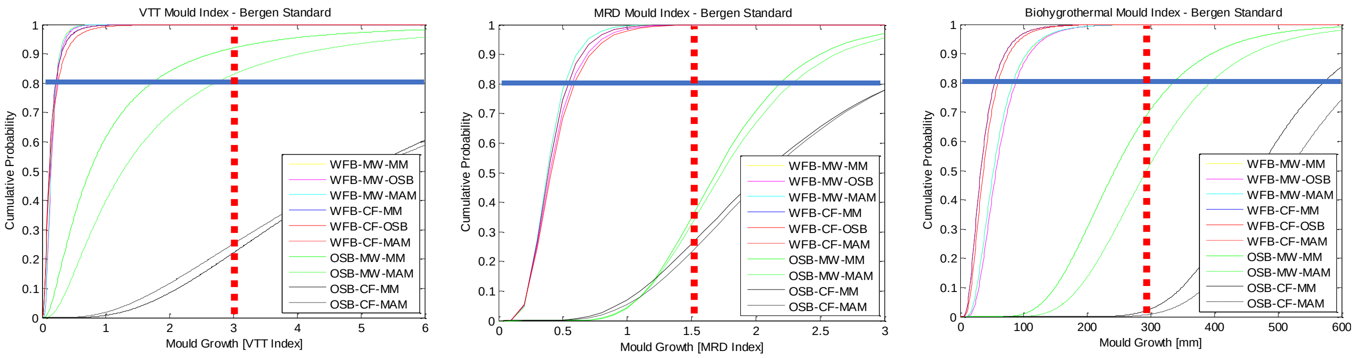

Figure 3 Use of three different mold models to assess the performance of ten variations of the same exterior wall

Categorization: drainage of water
- water can run off quite easily
- water can accumulate

Categorization: interference with barriers
- complete breakthrough
- disturbance is just at the surface
- geometrical changes

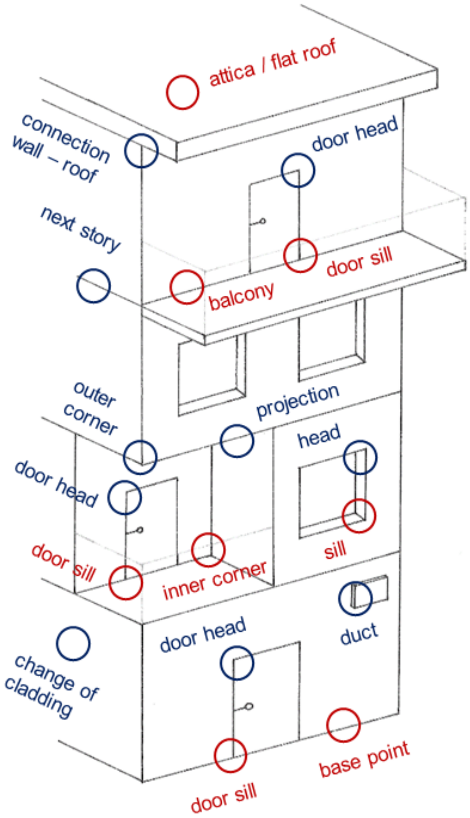

Figure 4: Categorization of details - drainage

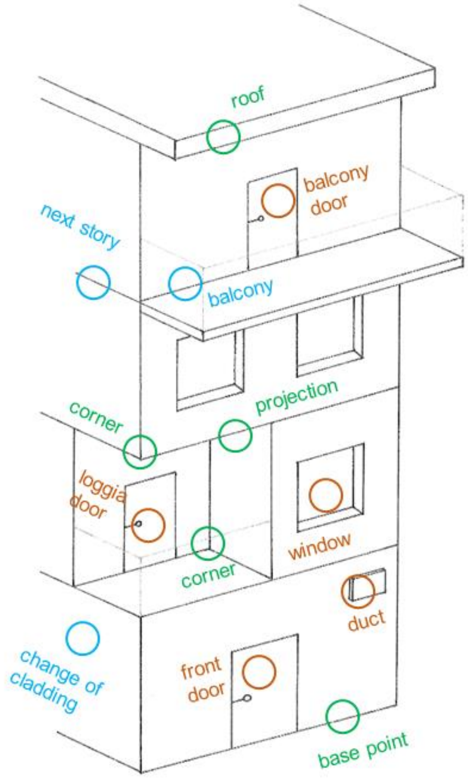

Figure 5: Categorization of details - barriers

Cost-benefit Analysis

The demonstration and evaluation of indirect consequences in terms of monetary and environmental impact makes obvious that the risk of moisture damages increases exponentially in tall timber buildings compared to single-family houses. In many cases the previously mentioned improvement of the basic facade composition or a little higher investment in adequate sealing solutions for joints reduces the risk by factor two to ten depending on the specific building and damage. Although a practical way of analysing cost-benefit was shown in Figure 6, the results are just generic due to the lack of appropriate and specific cost data. This is not major issue because these numbers are available in each company although they will not be available publicly.

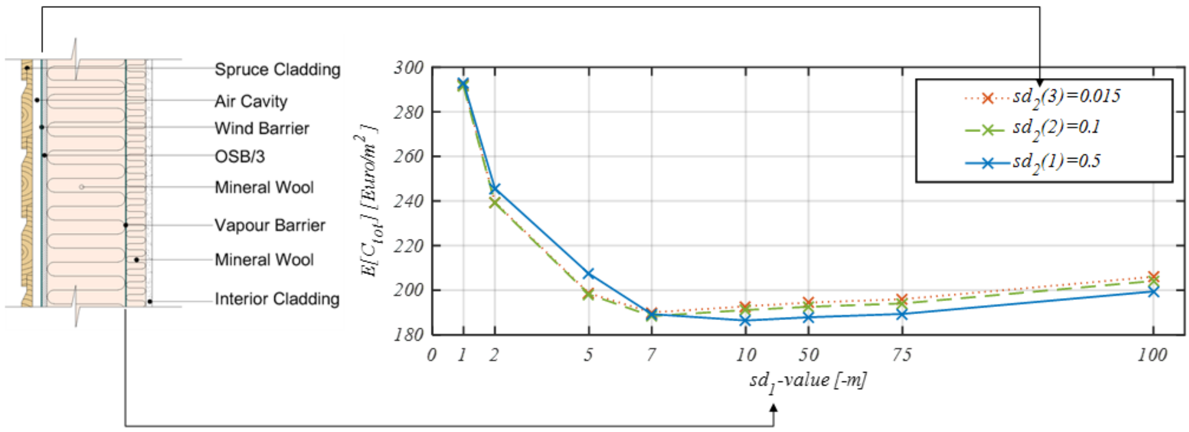

Figure 6. Cost-benefit and optimization analysis, total expected costs as a function of the wind barrier and vapor retarder

1.3 Conclusions

Based on the extensive research work done, it can be concluded that:

1. A risk-based approach for moisture-safe facade assessment was formulated (process of RiFa-Tool A),
2. RiFa-Tool A (numerical) is directly usable for prototype design (demonstrated in several simulations),
3. RiFa-Tool B (qualitative) can be used for development of alternative joint solutions,
4. Development of measurement protocol for event tree calibration,
5. Findings are relevant for construction companies due to the high monetary impact of possible moisture damages on envelopes of tall timber buildings.

1.4a Capabilities generated by the project

In risk model part A, a scientific approach, more suitable for research and development of components is developed. The performance assessment process employed as part of this RiFa-Tool A. The entire probabilistic-based approach is implemented in the form of a seamless and integrated parametric workflow^^ presented in Figure 7 by means of efficiently combining the MATLAB®, Python and XML codes. The seamless workflow enables an efficient conversion of the variability of the input parameters into a probabilistic representation of the output.

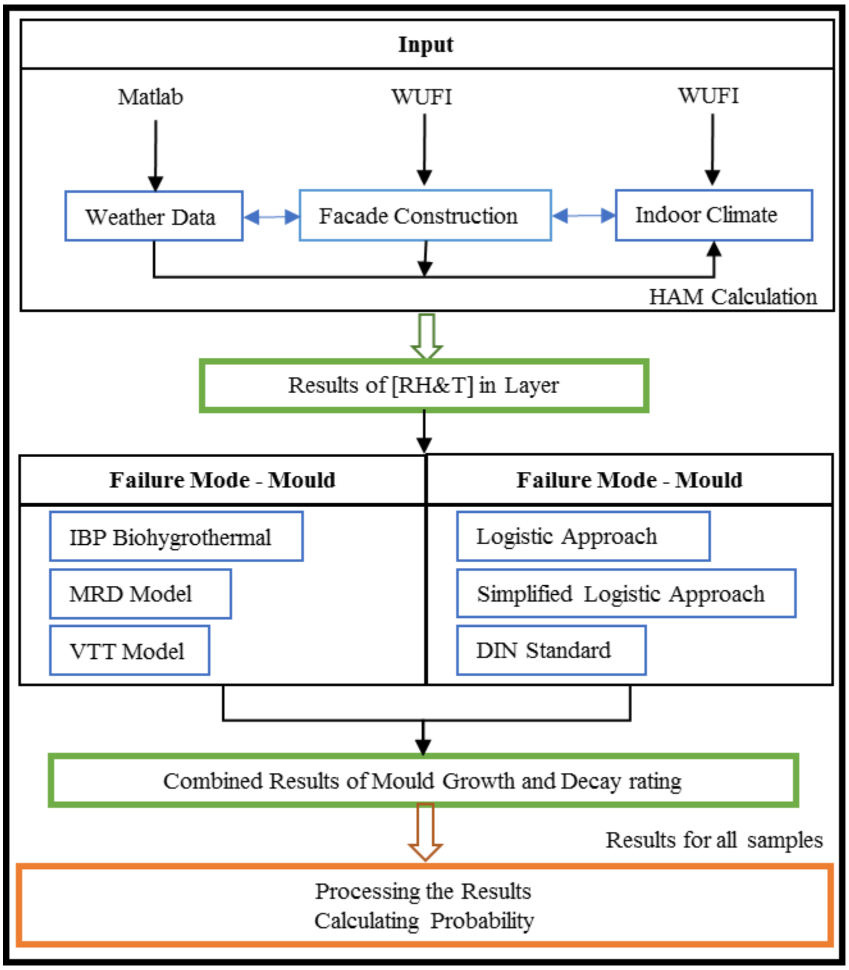

Figure 7. Schematic seamless and integrated workflow of the RiFa-Tool A (numeric)

The user of RiFa-Tool B can choose between two tools, depending on how much information he 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, see Figure 8. 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. The event tree method can be used as system analysis tool and for consequence identification. Additionally the event tree method gives a structured and generalized approach to solve different problems on joints or connections of components, which are highly prone to moisture leakage. It is a very good way to integrate load bearing, fire-safety, and sound transmission together with the moisture safety. The main advantage if its use is its flexibility; instead of solving problem with many different catalogues with details, which are not related to each other or already outdated. Under explicit event tree queries for failure, the tool will be able to serve work preparation and quality control. Hence, it will serve the improvement of quality in production, mounting, and avoidance of human error.

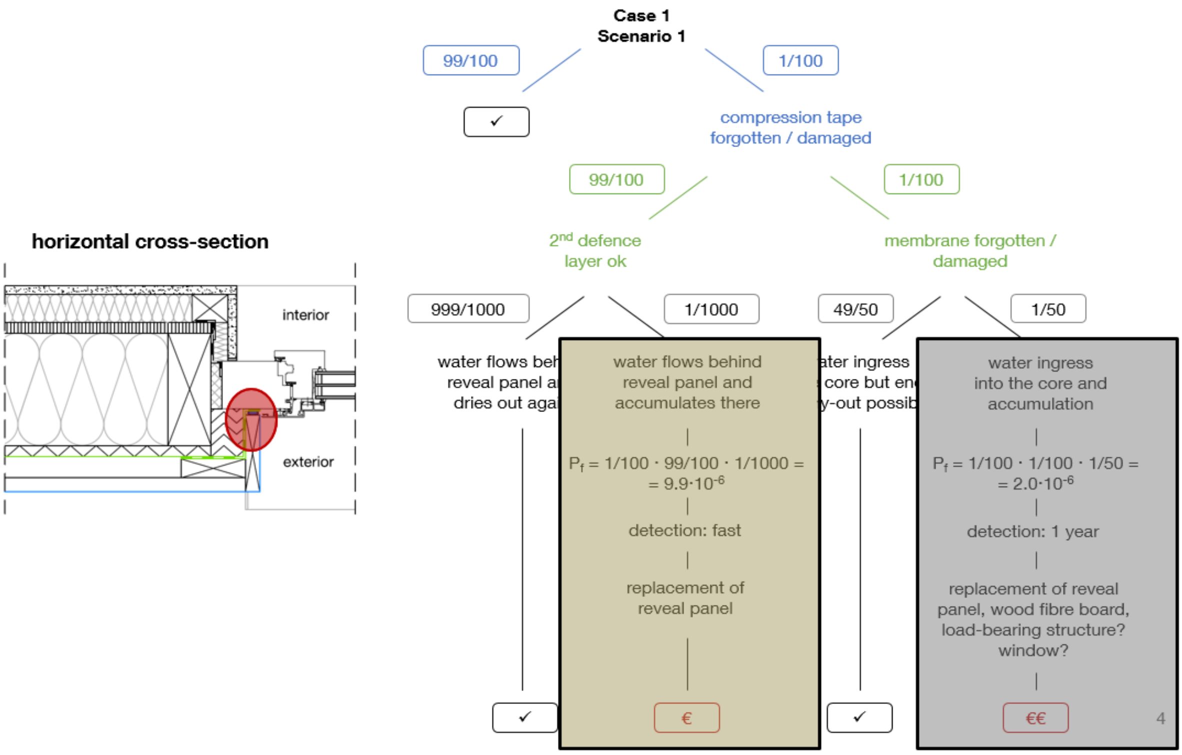

Figure 8 Event tree example of an exemplary window reveal, application of RiFa-Tool B (qualitative)

Future development potential:

a. Formulation of a semi-probabilistic dimensioning and design concept,
b. Embed risk-based approach deeper in LCA-analysis,
c. Expand the numerical RiFa-Tool A on critical connections and moisture risk areas,
d. Enhancement of RiFa-Tool B with empirical data.

The development of moisture safe joints especially for windows hit the nerve of time as one can see at the world's largest expo for construction products, BAU 2017, Munich. A lot of systems for sealing window sills and improved drip board integration were presented by almost all wood product companies and the timber construction industry suppliers. This went in line with the manufacture of several 1:1 demountable mock-ups of moisture safe window connections in Figure 9, built by TUM supporting a pro-active method in teaching and seminars.

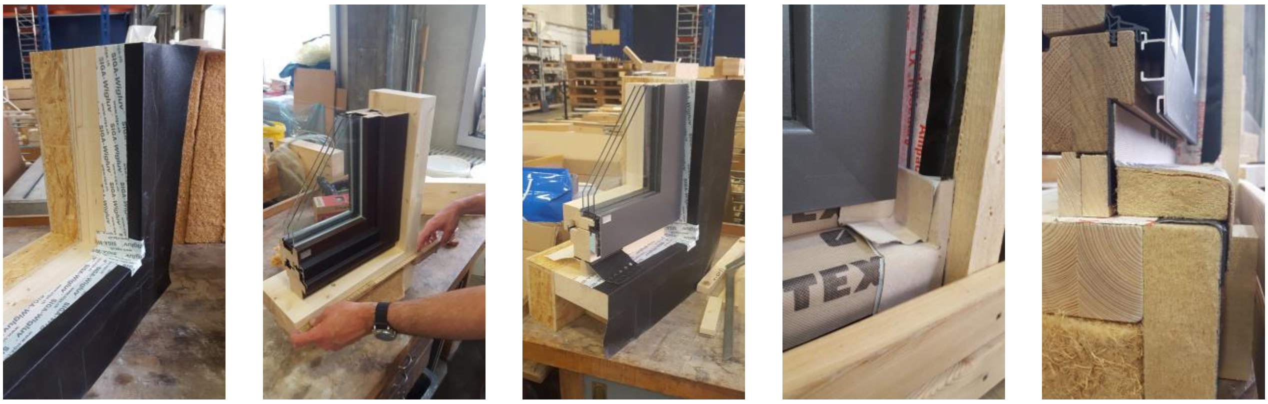

Figure 9. Moisture safe window sill picture series of 1:1 mock-up, sealing tapes are added with magnetic strips for easy demountability

1.4b Utilisation of results

Utilization of results have been succeeded throughout the project and several valuable publications in high-ranked scientific journals and presentations on renowned international conferences were held. The scientific dissemination was supported through a website, as well as through the project group of national experts and industry partners in seminars and teaching a young generation of engineers and scientists. Contacts to overseas researchers were established, due to their experience in and strongly support of a risk-based approach in moisture safety. Student and researcher exchange with international universities was realized.

Further topics, which should be addressed in future research, are the Indoor Air Quality (IAQ), especially the influence of mold on IAQ. This also includes the question, which type of mold is harmful to tenants, and which amount of mold is bearable. Together with the latter, the topic of the better understanding of scientific mold growth / development models is of importance. These models need better proof against reality. However, the empirical knowledge and data about mold occurrence in existing buildings is low. Therefore, an idea is to fill this gap with a field study supplying basic data about mold in building stock mainly made from wooden material but also of mineral-based buildings.
Another important topic is the missing knowledge about the real maintenance effort for buildings within a time span of 40 years. The required information comprise repair needs, maintenance and replacement cycles of claddings and entire building envelopes mainly on a wooden basis.
Finally yet importantly, the durability of existing wooden building stock is an important topic where we should learn from the past, by examining existing buildings, components, joints, and their materials, on an European level.

1.5 Publications and communication

a) Scientific publications

1. Articles in international scientific journals with peer review

*Ott, S., Tietze, A., Winter, S. (2015) Wind driven rain and moisture safety of tall timber houses – Evaluation of simulation methods, Wood Material Science and Engineering, 10 (3), pp. 300-311. DOI: 10.1080/17480272.2015.1068371.
*K. Gradeci, N. Labonnote, B. Time, and J. Köhler, "A probabilistic-based approach for predicting mould growth in timber building envelopes: Comparison of three mould models (Article in Press)," Energy Procedia, 2017.
K. Gradeci, N. Labonnote, B. Time, and J. Köhler (2017) Mould Models Applicable to Wood-Based Materials – A Generic Framework (Article in Press) Energy Procedia.
K. Gradeci, N. Labonnote, B. Time, and J. Köhler (2017) A probabilistic-based methodology for predicting mould growth in timber façade constructions, (manuscript submitted).
K. Gradeci, N. Labonnote, B. Time, and J. Köhler, "Mould growth criteria and design avoidance approaches in wood-based materials – A systematic review," (in English), Construction and Building Materials, Review vol. 150, pp. 77-88, 2017.
*Grynning S., Labonnote N., Time B. (2017) Moisture robustness of eaves solutions for ventilated roofs – experimental studies (manuscript submitted) Journal of Building Physics.

2. Articles in international scientific compilation works and international scientific conference proceedings with peer review

Ott S., Tietze A., Winter S. (2015) Wind driven rain and moisture safety of tall timber houses - Evaluation of simulation methods, in: Proceedings of Wood Building Nordic, 24. - 25. September 2015, Växjö.
K. Gradeci, N. Labonnote, B. Time, J. Köhler (2016) A proposed probabilistic-based design methodology for predicting mold occurrence in timber façades, in: Proceedings of WCTE 2016, Vienna.
*Tietze A., Boulet S., Ott S., Winter S. (2016) Consideration of Disturbances and Deficiencies in the Moisture Safety Design of Tall Timber Facades. , in: Proceedings of WCTE 2016, Vienna.
K. Gradeci, M. Baravalle, B. Time, and J. Köhler, "Cost-Optimisation for Timber Façades Exposed to Rot Decay," in 12th International Conference on Structural Safety & Reliability Vienna, 2017.
*Fufa S., Skaar C., Gradeci K., Labonnote N., Time B., Köhler J. (2017). Parametric LCA of a ventilated timber wall construction in tall timber buildings, in Proceedings of the 14th International Conference on Durability of Building Materials and Components, Ghent, Belgium, 29-31 May 2017.
Boulet S. (2017) Cost-benefit analysis of singular points on Tall Timber Facades (forthcoming). WoodRISE Conference 12.-15.09.2017, Bordeaux, France, http://wood-rise-congress.org/.
Winter S. (2017) Urban tall buildings (forthcoming). WoodRISE Conference 12.-15.09.2017, Bordeaux, France, http://wood-rise-congress.org/.
Ott S. (2017) Moisture safety of tall timber facades (forthcoming). Advanced Building Skins Conference, 3.-4.10.2017, Berne, Switzerland, http://abs.green/.

Winter S. (2017) Future development of wooden facades (forthcoming). Advanced Building Skins Conference, 3.-4.10.2017, Berne, Switzerland, http://abs.green/.
Grynning S., Labonnote N., Time B. (2018) Rain-tightness of door sill sealings – an experimental study (submitted), IBPC 2018, Syracuse, USA.

3. Articles in national scientific journals with peer review

-

4. Articles in national scientific compilation works and national scientific conference proceedings with peer review

Ott S., Tietze A., Winter S. (2015) Entwicklung eines semi-probabilistischen Feuchtesicherheitskonzeptes für hohe Holzfassaden, in: Konferenzband Bauphysiktage Kaiserslautern, 21. und 22. Oktober 2015, Kaiserslautern.
Ott S. (2016) Transfert d'humidité dans les bâtiments bois de grande hauteur: Projet TALL TIMBER FAÇADE, in: Proceedings of Forum Bois Construction 2016, Lyon, France, www.forum-boisconstruction.com

5. Scientific monographs

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6. Other scientific publications, such as articles in scientific non-refereed journals and publications in university and institute series

Sandberg K. (2015) Tall Timber Facades, Article in HusByggaren no 8.
Labonnote N. (2016) Knappe takutstikk kan også gi god beskyttelse mot regn og vind, Article ByggeIndustrien, No. 16.

a) Other dissemination

BayFOR News 10-2014: Zwei ERA-Net-Projekte zum Thema Holz erfolgreich gestartet – TallFacades, October 2014, p.3.
BayFOR Jahresbericht 2014: Forschung trifft Innovation. 2015. p. 29.
TallFacades project presentation, Woodwisdom-Net seminar Stockholm, 2014.
Norwegian Industry workshop, Norway, organized by SINTEF, NTNU, ISOLA, Overhalla. 12.08.2014.
Norwegian Industry workshop, Norway, organized by SINTEF, NTNU, ISOLA, Overhalla. 24.03.2015.
TallFacades project presentation, Woodwisdom-Net seminar Zürich, 2015.
National meetings with insurance company Gar-Bo. organized by SP, Moelven, Martinsons. Sweden, on three occasions: 25.11.2015, 13.04.2016, 16.05.2016.
National Industry workshop, TallFacades Experten-Workshop, organized by TUM, Munich, Germany, 09.06.2016.

Norwegian Industry workshop, Norway, organized by SINTEF, NTNU, ISOLA, Overhalla. 01.09.2016.
TallFacades project presentation, Woodwisdom-Net seminar Edinburgh, 2014.
Final symposium Tall Timber Facades – presentation of results. organized by TUM. Oskar-von-Miller Forum, München, Germany, 21.06.2017.
ZNB Symposium: Herausforderungen feuchtesicherer Gebäudehüllen, 23.06.2017. TUM Centre for Sustainable Building.

1.6 National and international cooperation

Internal control and organization was endured by an updated project-plan related to progress in milestones and tasks. Additionally the project emphasizes:

- Organization of common meetings with a workshop character,
- Project outcome is clearly grasped and communicated in the meeting minutes,
- Sharing of all information on the projects common project space (cloud / webdisk)
- Continuous exchange of information and progress in-between the physical meetings by regular web meetings of the group and direct communication between researchers as well,
- Constant improvement and development of the project idea in exchange with other institutions, industry representatives and experts sharpens the topic,
- Early conceptualization of project results during the proposal stage stimulates the final outcome.

Lessons learnt from discussion with the timber construction industry:
The timber construction industry has to fulfil triple constraint for every new commercial project they deliver: *time – cost – product* (scope / quality). Timber construction industry struggles hard to be competitive and achieve the triple constraint. Therefore, TallFacades worked on cost-efficient measures with a performance based risk-oriented approach:

- cost for moisture safety identified by TallFacades: additional planning costs due to higher safety and durability requirements for tall timber buildings, but
- cost reduction potential due to RiFa-Tool: enabling of performance based safety levels in relation to the location / climate exposure / durability requirements, less faults, lower insurance rate, reduced warranty claims.
- long term cost gain: for industry, a wooden building with low degradation linked to moisture (from simple aesthetic degradation up to the fail of facade elements) allows to keep a positive image and reputation.
- time effort: additional time demand for performance based design, additional quality control and protection measures (layers, façade types).
- time reduction potential: performance based façade safety rules enable simplified construction (in parts of façade) at same level of performance;
- product improvement: by quality control through moisture safety planning process steps, TallFacades execution rules, and a focused education / training program.
- These findings were further refined during the project and incorporated into the applicability of RiFa-tool.

Project partner RISE (SP) started to ask about frequent damages in the building envelope from the Swedish insurance company Gar-Bo. Gar-Bo insures mostly small wooden houses and not high-rise wood buildings. Nevertheless, Gar-Bo offers data about damage cases from their statistic and investigates various types of damages. SP is going to use the result as “verification” of the assumptions to the LCA and LCC models.

Cooperation with non-partners:

- in cooperation with the TUM Practical Research Experience Program (TUM PREP) TallFacades offers an exchange program for students from North America and had a visitor from Alberta University, Edmonton (Canada)
- University of Bilbao (UPV/EHU), Escuela Técnica Superior de Ingenieria Bilbao, planned PhD student exchange in 2016 failed due to refusal of grant from German academic exchange program,
- ongoing contacts with WUFI® software developers (Fraunhofer Institute for Building Physics, Holzkirchen, Germany), their engagement in latest mold model implementation led to the decision for WUFI as hygrothermal simulation tool,
- national survey on moisture safety of wooden buildings led to an industry workshop,
- strengthening of dissemination by national trade agencies and timber construction companies through industry partners (RUBNER, Eternit, Moelven, Martinsons, ISOLA, Overhalla) as well as through personal networks, to explain and make aware wood construction companies for the moisture safety topic of TallFacades.