Online supplementary information for paper

CRACK SIZE AND MOISTURE PROBLEMS COMPARING THERMALLY MODIFIED AND NATIVE SPRUCE WINDOW FRAME PROFILES

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Modelling parameters

The boundary conditions used in the simulations are listed in Table S1.

Table S1: Boundary conditions

	Temperature [°C]	Surface heat transfer coefficient [W/m^{2}K]	Relative humidity [%]	Water vapour diffusion transfer coefficient [s/m]	Short-wave direct and diffuse radiation [W/m^2]	Long-wave radiation [W/m^2]	Rain [l/m^{2}h], Wind direction [Deg], Wind, velocity [m/s]
Outside	Ljubljana (1)	10.5 (3)	Ljubljana (1)	7.5×10^{-8} (3)	Ljubljana (1)	Ljubljana (5)	Ljubljana (1)
Inside	Ljubljana (2)	8 (vertical surface)(3) 4 (corner including vertical part)(3)	Ljubljana (4)	2.5×10^{-8} (3)	/	/	/

(1) 5-years half-hourly climate data for the period from 1st January 2017 to 1st January 2022 for the location Ljubljana-Bežigrad; short-wave radiation and wind-driven rain were taken for the surface orientated to the north.

(2) calculated according to EN 15026:2023.

(3) typical values from EN 15026:2023, Table 2. For the outside, only convection part (hc) is taken into account because the outside longwave radiation is calculated separately. The value for the thermal resistance of the air in the corner of the profile was taken from ISO 13788:2012, where the value is for the corner in the room.

(4) calculated according to EN 15026:2023. The outer temperatures, needed for calculation, were taken from (1). Class 3 of "normal moisture load" was taken into account;

(5) calculated from the data for 7-14-21 cloud covering for the period from 1st January 2017 to 1st January 2022 for the location Ljubljana-Bežigrad for vertically oriented surface according to the reference: Walton G. N., 1983, Thermal Analysis Research Program Reference Manual, NBSSIR 83-2655, p.21 (linear interpolation is used for intermediate hours).

Table S2 shows the material properties of native sprucewood and thermally modified sprucewood.

Table S2: Material properties of wood types

	Thermal conductivity λ [W/mK]	Water vapour diffusion resistance factor μ [/]	Specific heat c_p [J/kgK]	Density ρ [kg/m^3]	Porosity θ_{eff} [m^3/m^3]	Liquid water conductivity Kl_{eff} [s]
Native Norway spruce	0.11 [1]	50 (wet-cup), 20 (dry-cup) [2]	1600 [2]	470 [4]	0.728 [3]	From 0 for dry material to 9.2×10^{-10} for 100% moist material [3]

Thermally modified spruce	0.09 [1]	50 (wet-cup), 20 (dry-cup) [2]	1600 [2]	410 [5]	0.728 [6]	Value from [3] with scaling diminished for a factor of 3,80 [7]

[1] *from ISO 10077-2:2017 (native spruce) and from Ugovšek A., Šubic B., Rep G., Humar M., Lesar B., Thaler N., Brischke C., Jones D. and Lozano J. I. 2016. Performance of windows and facade elements made of thermally modified Norway spruce (Picea abies) in different climatic conditions. World Conference on Timber Engineering. Vienna, 2016 (TM spruce)*

[2] *from EN ISO 10456:2008.*

[3] *taken from Delphin 6.1 for »Spruce-tangential« (identification number - ID of the material in the material database of Delphin 6.1 is 695).*

[4] *from Wagenführ, R. (2000) Holzatlas Fachbuchverlag, Leipzig, München.*

[5] *from Humar M., Repič R., Kržišnik D., Lesar B., Cerc Korošec R., Brischke C., Emmerich L., Rep G. 2020. Quality Control of Thermally Modified Timber Using Dynamic Vapor Sorption (DVS) Analysis. Forests. 11. 666.*

[6] *value for spruce from [14] was adopted, although the value for TM spruce is a bit bigger. But, relevant data for TM spruce was not found.*

[7] *scaling factor of effective liquid water conductivity from the Delphin 6.1 material with ID = 695 was adjusted to get the best fit of numerical and experimental results (the average values of the latter). Along with all the functional dependence of liquid water conductivity on Rh, only a single scaling factor was used for each of the two types of wooden materials. The region up to (or slightly above) 10 % of the mass increase due to liquid water intake was adopted for the spruce with and without coating layers (the exact value depends on the "location" of the first measured time point after the value 10 % of MC was reached) and 5% (or closer) for the TM spruce.*

In Figure S1 the sorption curves, used in simulations for spruce and TM spruce are presented. They are combined from 2 curves:

1. The desorption curves, measured for relative humidity values up to 95 % with the step of 5 %. The curve for spruce gives higher MC values than the Delphin built-in curve for material with ID = 695. It is, therefore, more unfavourable (shown in Figure 3).
2. The Delphin built-in curve for spruce with ID = 695 for relative humidity values above 95 %.

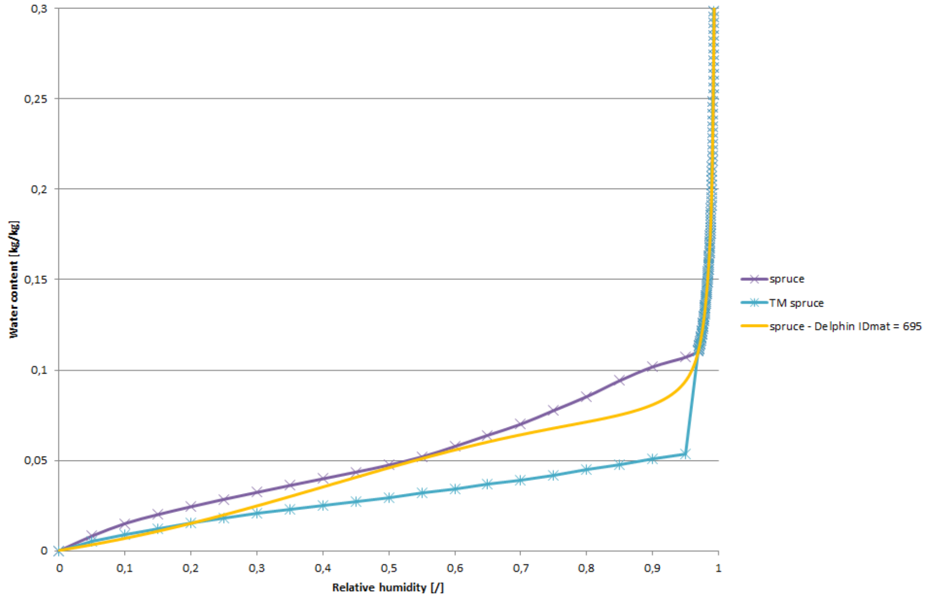


Figure S1: The sorption curves for spruce (purple) and TM spruce (light blue), used in the simulations, as well as the Delphin built-in curve for material with ID = 695 (yellow). The latter is glued to the measured points at 95 % of the RH and used for both materials above 95 % of RH. MC of 18 % is reached at 98.8% relative humidity and MC of 20 % is reached at 99.0 % relative humidity.

Material properties of TM spruce are the same as for spruce, with two exceptions:

- water vapour diffusion resistance factor was directly measured;
- liquid water conductivity was obtained when fitting numerical simulation results to experimental ones (with experimentally measured spruce with the density of 450 kg/m3 and TM spruce with the density of 412.5 kg/m3) when varying the scaling factor of liquid water conductivity of Delphin's material with ID = 695 – only one scaling factor is used for the whole function. When simulating the experimental setup, the K_l function from Delphin's material with ID = 695 was uniformly diminished by a factor of 66 (=$10^{1.82}$) for native spruce and for a factor of 251 (=$10^{2.4}$) for TM spruce.

The resulting values for standard and TM spruce are presented in Table S3.

Table S3: S_d values and scaling factor for liquid water conductivity of Delphin's material with ID = 695 (for spruce the data are adopted from Vidmar G., Jukić M. 2022. The influence of cracks in the protective coating on the hygrothermal behaviour of wooden window frame profiles. Advanced building skins: 17th Advanced Building Skins Conference & Expo. 20-21. October 2022. Bern, Switzerland. Lucerne: Advanced Building Skins. p.p. 264-273.)

	Native spruce with coating 1	Native spruce with coating 2	TM spruce with coating 1	TM spruce with coating 2
S_d of coating layer [m]	1.22	1.95	1.41	2.41
A factor of diminishing of liquid water conductivity of a surface layer in comparison to Delphin's material with ID = 695 *	501 (=$10^{2.7}$)	891 (=$10^{2.95}$)	1318 (=$10^{3.12}$)	1445 (=$10^{3.16}$)

When simulations on window frame were performed, the Delphin's built-in K_l factor was used for spruce, and diminished with factor 3.8 (see Table S2) for TM spruce, thus not the same values as when fitting experimental results. The reason is that the simulations are considered to be valid for a typical wooden profile from native spruce and TM spruce, not predominantly for the specific measured one.

Modelling uncertainties

The calculated deviations of maximum and average MC in the model with native spruce without a surface crack at day 1501, where the maximum of locally maximum MC value during all the simulation time appears, are presented in Table S4. The maximum value of MC with original parameters for spruce (Tables S2 and S3) is 0.153 kg/kg. For vapour diffusion, sorption and liquid water conductivity the whole curves were recalculated. Porosity was not examined, because it directly influences the Kl and sorption curve.

Table S4: Variation of output maximum and average MC values at exposed tooth when varying input material characteristics from Table S2 for ± 10 % in the model with spruce and without surface damage for day 1501.

Upper number = max. value **Lower number = avg. value**	Thermal conductivity λ [W/mK]	Water vapour diffusion resistance factor μ [/]	Specific heat c_p [J/kgK]	Density ρ [kg/m^3]	Sorption curve θ [kg/kg]	Liquid water conductivities Kl [s] - material and surface coating	Surface vapour resistance factor Sd [m]
Variation of the parameter for -10 %	- 0.3 % - 0.4 %	- 0.2 % < 0.1 %	< 0.1 %	+ 11.1 % + 11.1 %	- 12.5 % - 10.9 %	- 0.8 % - 0.9 %	+ 0.2 % < 0.1 %
Variation of the parameter for +10 %	+ 0.3 % + 0.4 %	+ 0.2 % < 0.1 %	< 0.1 %	- 9.1 % - 9.1 %	+ 89.0 % + 37.6 %	+ 0.3 % + 1.1 %	- 0.1 % < 0.1 %

Mould growth modelling parameters

The VTT mould growth model was the first we used. It is defined by mould growth index M, where M = 1 means the start of the mould growth and M = 3 means that the surface mould becomes visible. For both materials the material class "Sensitive" (s) is taken into account, thus $k_1 = 0.578$ or 0.386 (depends if M is lower/higher than 1, respectively), A = 0.3, B = 6, C = 1.5 and $RH_{min} = 80$ % (from Ojanen T., Peuhkuri R., Viitanen H., Lähdesmäki K., Vinha J., Salminen K. 2011. Classification of material sensitivity - New approach for mould growth modeling. 9th Nordic Symposium on Building Physics - NSB 2011). Because the class was introduced for cement or plastic-based materials or materials from mineral fibres, we do not know a reason why for TM spruce a medium resistance class could be adopted. The surface class "very sensitive" is taken into account for the damaged surfaces, whereas "sensitive" surface class is for undamaged surfaces. For the decline class, "Almost no decline" ($C_{mat} = 0.1$) was used in all cases. Additionally, also "Very sensitive (vs)" class with the parameters $k_1 = 1$ or 2, A = 1, B = 7, C = 2 and $RH_{min} = 80$ %, and "Medium resistant (mr)" class with the parameters $k_1 = 0.072$ or 0.097, A = 0, B = 5, C = 1.5 and $RH_{min} = 85$ % were used.

For the second model we used isopleth or biohygrothermal model. Substrate category I and mould class A was adopted for isopleth modelling. For biohygrothermal mould growth modelling the WUFI-Bio option “Indoor surface or positions in contact to indoor air” was chosen with 50 % initial RH in the spore. A substrate category I was applied also for biohygrothermal modelling, whereas for the comparison purpose additionally substrate class II was used for TM sprucewood. Although the consideration of TM and native spruce with different substrate classes cannot be fully justified, it seems the right way of reasoning in order to improve the comparative modelling of both types of woods.

Results for undamaged model – isopleth mould growth model

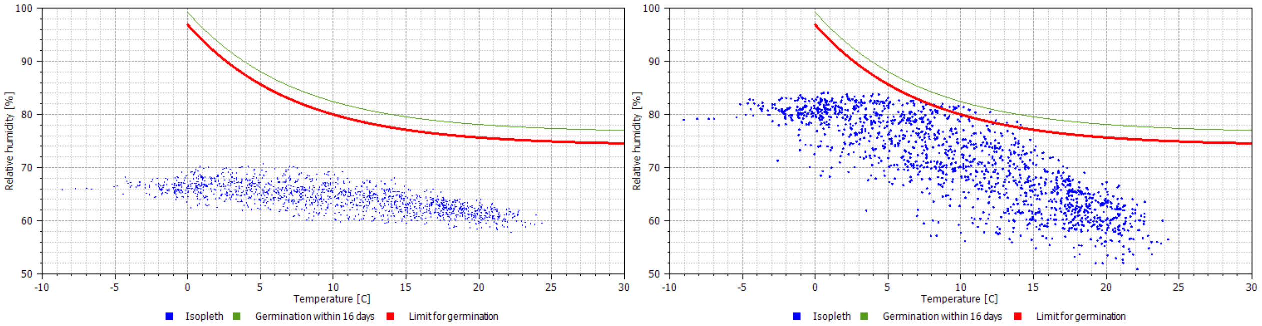
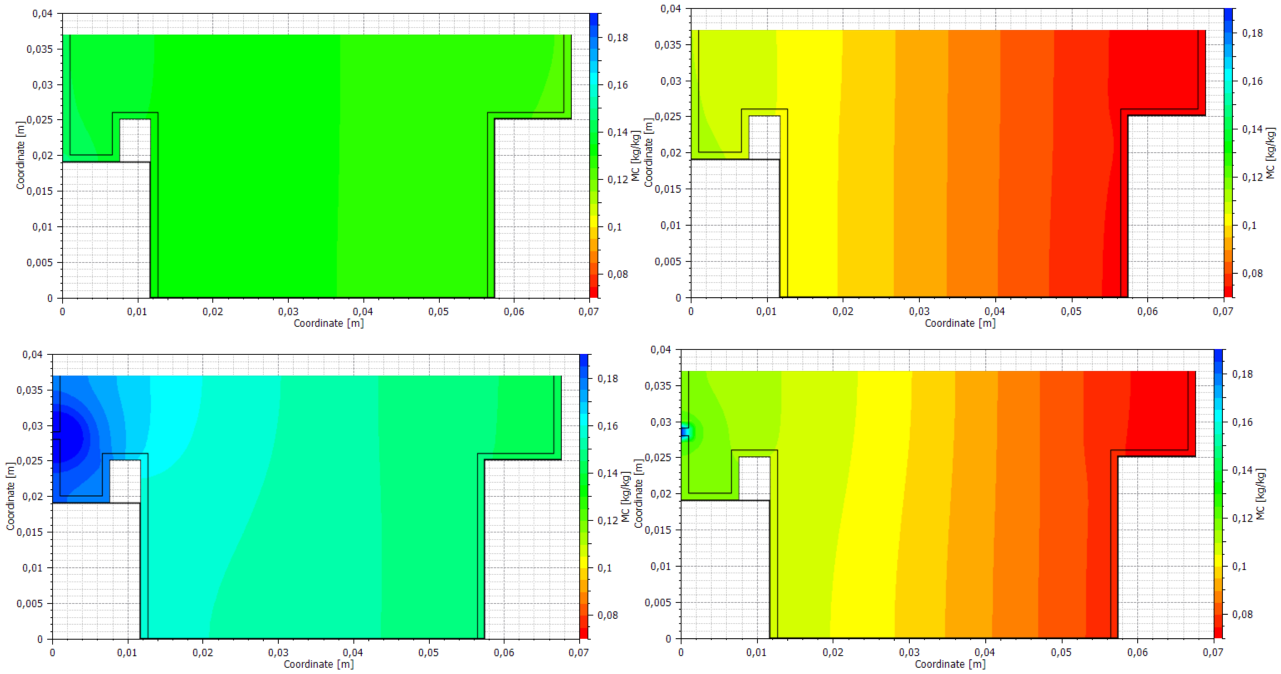


Figure S2: Isopleth mould growth risk model with undamaged coating 1 for the native (left) and TM spruce (right) at the location of the vertically exposed side of the problematic tooth (marked with a green ellipse in Figure 4). Substrate category I and mould class A are adopted.

Results for damaged model – comparison of moisture profiles at the critical day with increasing cracksize



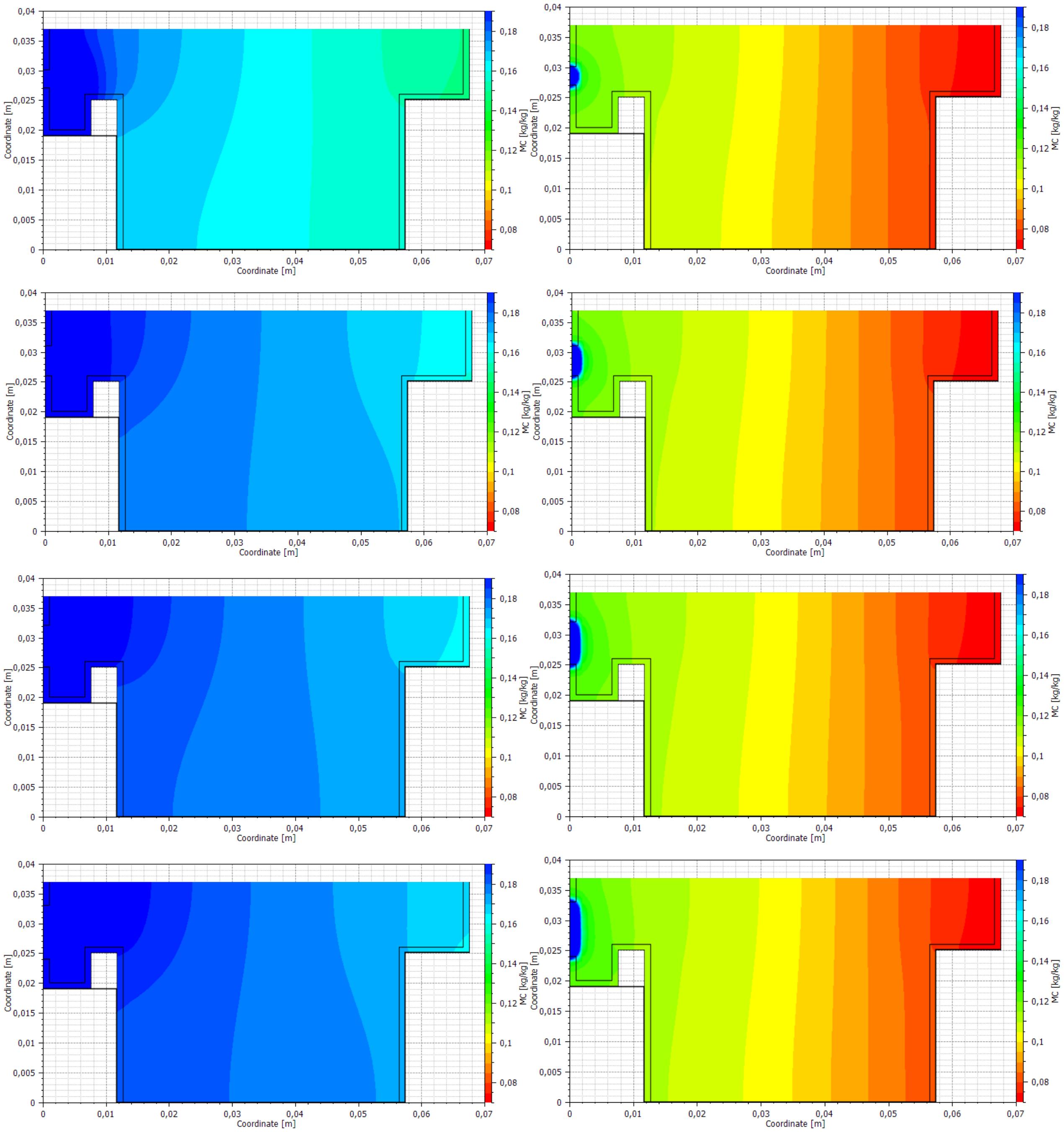


Figure S3: MC profiles in the model with native spruce (left plots) and TM spruce (right plots) with surface coating 1 at day 1795,5 after the start (5th winter) of simulations: models without damage (upper 2 plots) and models with the damaged region in the height of 1 mm, 3 mm, 5 mm, 7 mm and 9 mm (other plots). The problematic (critical) regions are shown in blue. The day 1796 is the day of the maximum local maximum MC in native and TM spruce during the whole simulation time.

Results for damaged model – biohygrothermal growth model

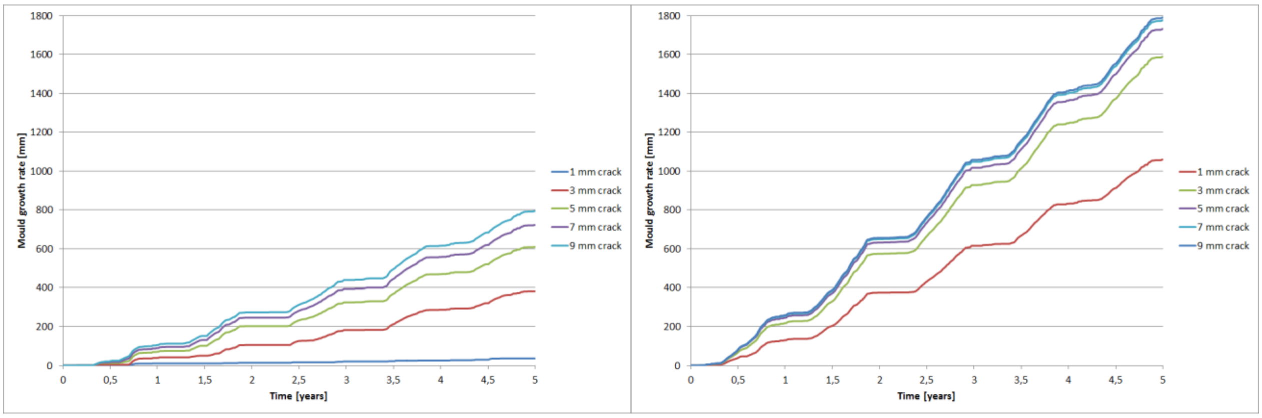


Figure S4: Biohygrothermal mould growth rate with damaged coating 1 for the native *(left) and TM spruce (right) for the crack sizes of 1 mm, 3 mm, 7 mm and 9 mm at the center location of the vertically exposed side (marked with a green ellipse in Figure 5). Substrate category I, initial RH in the spore 50 % and the WUFI-Bio option "Indoor surface or positions in contact to indoor air" were chosen.*

Results for damaged model – VTT mould growth model

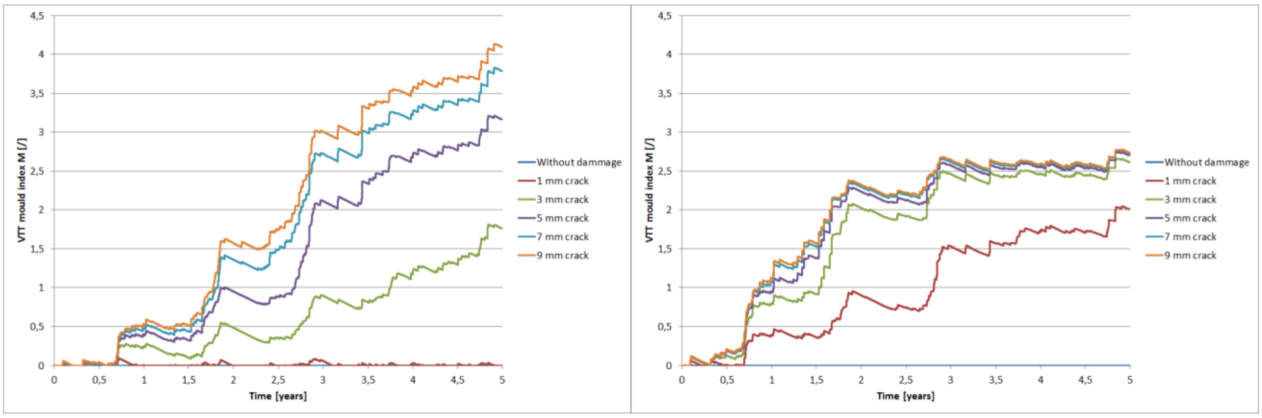
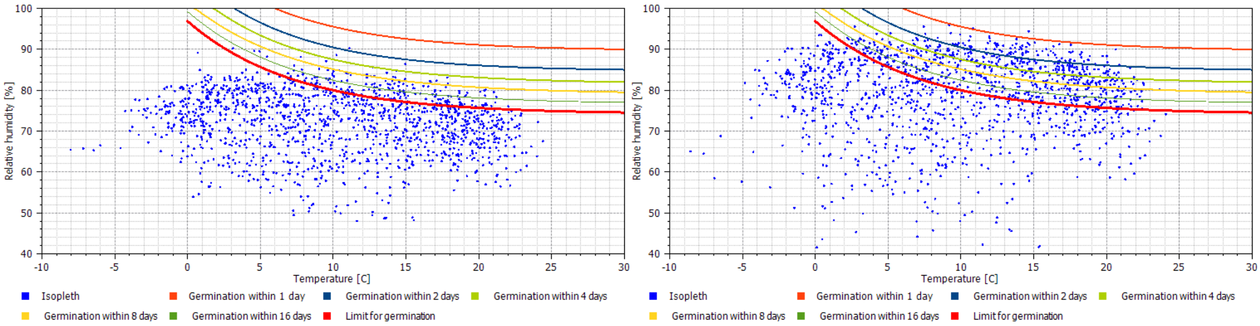


Figure S5: VTT mould growth index for location marked in Figure 5 with green ellipse for the native *spruce (left plot) and TM spruce (right plot) applied in the model with damaged coating 1. Results of the model with the damaged region (crack) in the height of 1 mm, 3 mm, 5 mm, 7 mm and 9 mm as well as results with the undamaged coating are shown. "Very sensitive" surfaces and "almost no decline" option are taken into account. For spruce "very sensitive" material and for TM spruce "medium resistant" material was used.*

Results for damaged model – Isopleth mould growth model



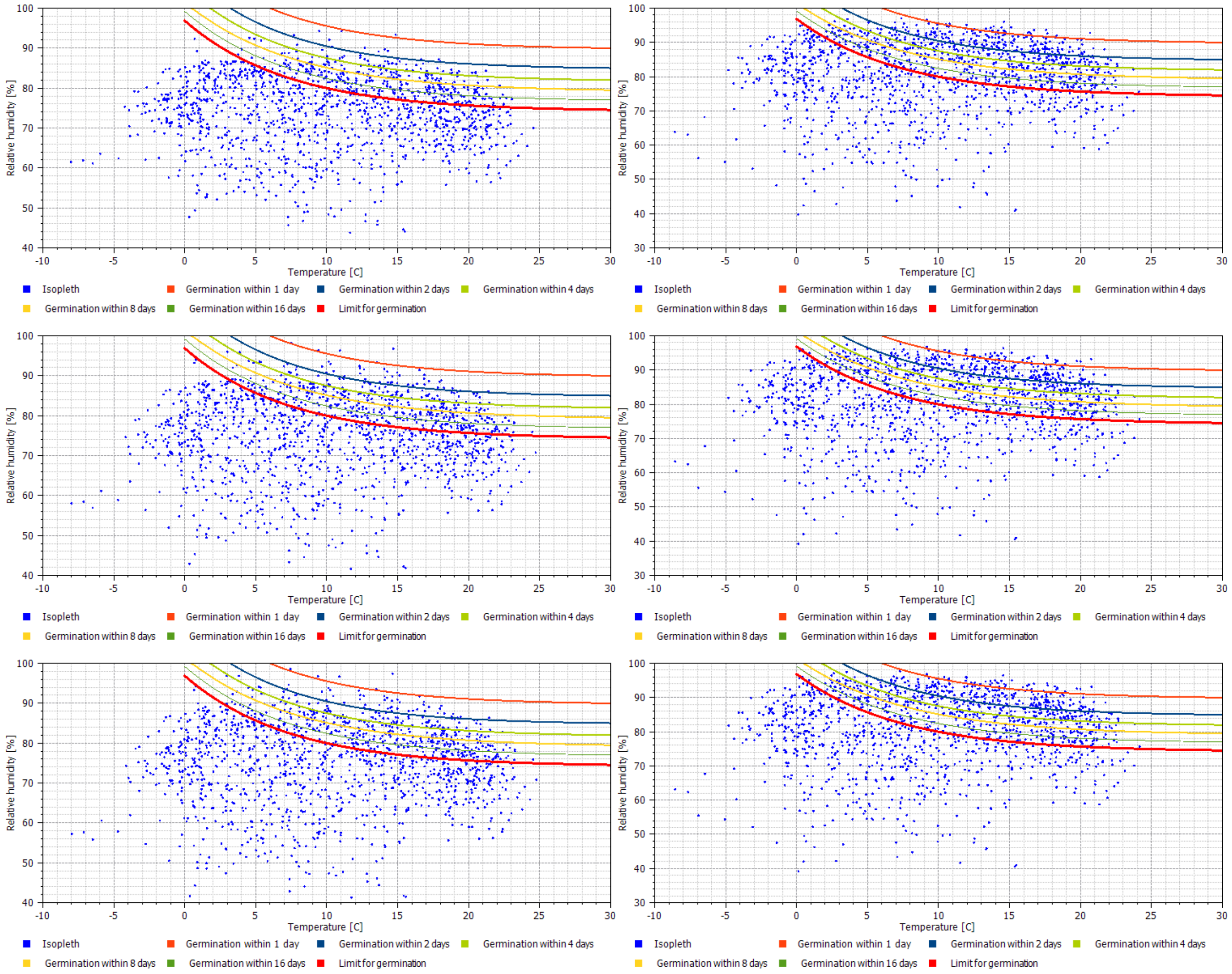


Figure S6: Isopleth mould growth risk model with damaged coating 1 for the native (left column) and TM spruce (right column) for the crack sizes of 1 mm, 3 mm, 7 mm and 9 mm at the location of the vertically exposed side of the problematic tooth (marked with green ellipse in Figure 2 – right plot). Substrate category I and mould class A are adopted.