Probabilistic Risk Assessment Applied to Biological Growth on External Surfaces with ETICS

Nuno M.M. Ramos[1], E. Barreira[1], M.L. Simões[1] and J.M.P.Q. Delgado[1]
[1]LFC Building Physics Laboratory, Civil Engineering Department, Faculty of Engineering of the University of Porto, Rua Dr. Roberto Frias, s/n, 4200-465 Porto, Portugal

ABSTRACT

External thermal insulation composite systems (ETICS) for walls are a very interesting technology but, despite its thermal advantages, ETICS is faced with a very serious problem: the defacement caused by biological growth. At this moment, no simple process has yet been developed to predict the risk of ETICS defacement, which may be used by designers, engineers and the building industry.

A methodology of probabilistic risk assessment of biological growth on ETICS exterior layer will provide guidelines to help in decision. In this work, a risk analysis approach has been improved and evaluated in a case study with ETICS. The scope of the risk analysis was established to define its main purposes when applied to ETICS. Secondly, a qualitative probabilistic analysis was done to determine the variables and parameters that are mandatory in ETICS defacement and should be considered in the risk analysis. Data regarding the mandatory variables and parameters in ETICS defacement was collected in order to establish a probabilistic approach of its variation and, a quantitative probabilistic risk analysis strategy is presented based in Monte Carlo simulations.

Finally, a meta-model, Response Surface Methodology, was developed and compared with a hygrothermal simulation tools, for assessing biological growth on ETICS as a function of exterior temperature, exterior relative humidity and atmospheric radiation. Response Surface Methodology is one of the most widely-used meta-models, which refers not simply to the use of a response surface as a multivariate function but also to the process for determining the polynomial coefficients themselves.

INTRODUCTION

The defacement of ETICS has been studied by building physics as its caused by a combination of hygrothermal conditions that can be simulated with complex HAM modelling. Several studies have contributed to the understanding of the microbiological growth in ETICS (Kunzel and Sedlbauer 2001) and mathematical models for simulation are available (Kunzel et al. 2002). No simple process has yet been developed to predict the risk of ETICS defacement, but the authors believe that a risk analysis addressing the uncertain nature of the problem can support the implementation of ETICS solutions, with a reasonable knowledge of their feasibility and therefore avoid applications with a high probability of poor behavior. Risk assessment application to building physics problems is gaining acceptance and several articles have addressed the subject, using different approaches (Pietrzyk and Hagentoft 2008, Pallin et al. 2011, Zhao et al. 2011))

The authors are developing a methodology for risk analysis of ETICS defacement, derived from the framework proposed by Kalagasidis and Rode (2011). The latter can be applied to the probabilistic assessment of several issues in building physics design such as energy performance, durability, thermal comfort or IAQ. Part of that methodology is a quantitative risk analysis that is explored in this article.

FRAMEWORK

The problem to be studied is the evaluation of the risk of ETICS defacement due to microbiological growth. The risk is the probability of occurrence of defacement, the undesired consequence of a scenario that must be defined. The façade system under study is presented in Figure 1. The context of the problem inspires an expression of results based on scenarios comparison and not so much in the expression of the probability of failure, as failure would be hard to determine even without its stochastic nature. A decision was made to express the results of the analysis as distributions for parameters that would represent an increasing risk for the system.

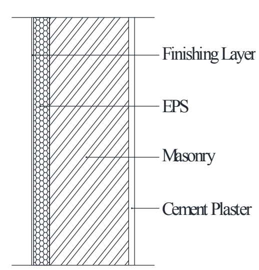

Figure 1 Façade system

The analysis of the problem can benefit from building a fault tree, presented in Figure 2.

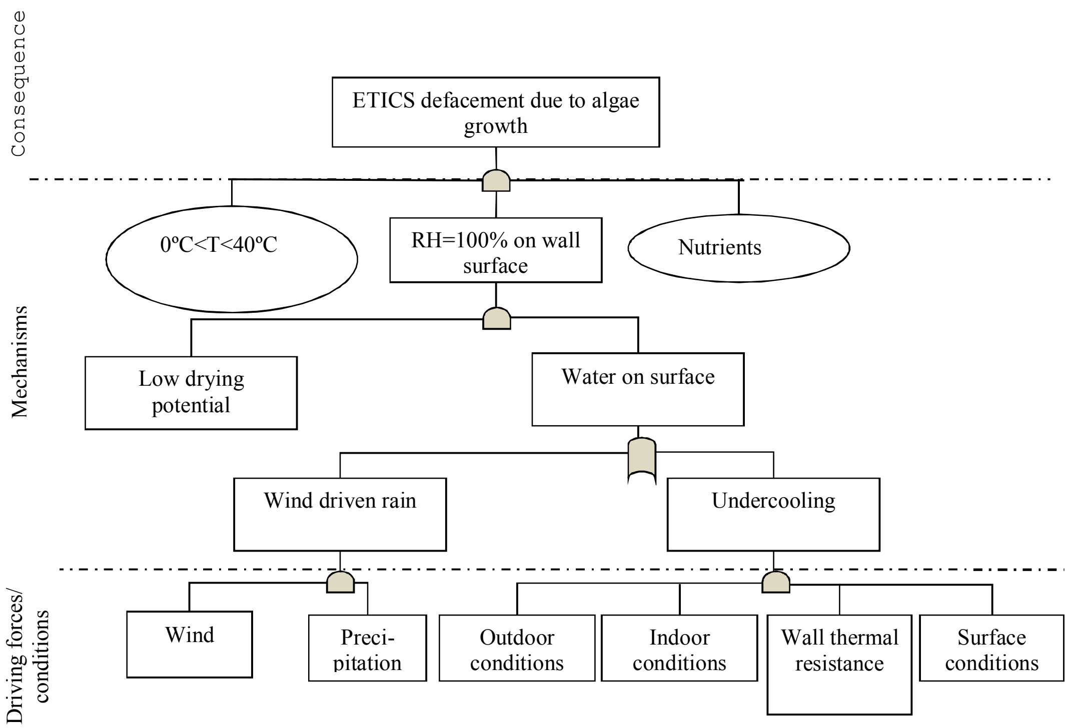

Figure 2 Fault Tree Analysis (FTA) for ETICS defacement (inspired in Pallin 2012).

After the FTA is possible to address the criteria for evaluating the risks a specific façade would be facing. A favourable temperature for algae growth must exist. The values referred in the FTA can be found in Venzmer (2001) and Haubner et al. (2006). The existence of nutrients is also mandatory (Lengsfeld and Krus 2004). The relevance of algae growth for ETICS defacement and its dependence on RH~100% was explored by Haubner et al. (2006).

To evaluate the risk of defacement two different criteria were explored.

The first criterion corresponds to the number of hours the of RH=100% on the wall surface.

The second criterion is more elaborate and corresponds to the quantification of undercooling, a relevant process to the amount of water on the surface. Exterior surface condensation can be analysed using psychrometry principles. When water vapour partial pressure of the air near the surface is greater than the water vapour saturation pressure at the surface, condensation will occur.

According to Zheng et al. (2004) the difference between the water vapour partial pressure in the air close to the surface and the water vapour saturation pressure on the surface may be called Condensation Potential (CP), which implies condensation for positive values.

$$CP = P_v(air) - P_{sat}(surface) \qquad (1)$$

where P_v(air) is the water vapour partial pressure in the air close to the surface in Pa and P_{sat}(surface) is the water vapour saturation pressure on the surface in Pa.

The product of positive CP ($CP_{(>0)}$, in Pa) by the corresponding interval of time ($\Delta t_{CP(>0)}$, in h) may be called Condensation Potential Equivalent (CPE, in Pa.h). The accumulated value of positive Condensation Potential Equivalent [(CPE > 0)accum] during a certain period of time allows estimating the amount of water vapour that is available to condensate in that period of time. It must be stated that CPE or its accumulation is not useful as a parameter for modelling algae growth being instead a risk indicator. However the aim of the proposed probabilistic model is only to compare risks.

METHOD

The overall idea is that, at city level, the risk for ETICS defacement is intended, implying a wide variability for simulation parameters. The chosen method for quantitative analysis corresponds to a Monte Carlo simulation with the following features:

- Each Monte Carlo set produces samples of CPE values (monthly average) or N values (number of hours with RH=100%) of a wall in a given scenario following a specific probability distribution;

- Each scenario includes the wall represented in Figure 1, the weather file of a specific city, a fixed indoor climate of T= 20 ºC and RH = 60% and a defined range for the variation of each stochastic parameter;
- The high amount of simulations needed is computed in a metamodel, shortening the time demand for the complete analysis;
- The metamodel is built with the aid of detailed HAM simulations using WUFI, including wind driven rain and explicit radiation exchange.

SIMULATION PARAMETERS

The knowledge on simulation parameters is very important to decide the level of detail that can be implemented and to do the actual calculations. In this case, the system characteristics were known in a level of detail compatible with WUFI software. The surface coefficients are listed in Table 1.

Table 1
Surface transfer coefficients

Coefficient	Numerical value
Exterior convective heat transfer coeff. [W/m2.K]	Leeward: $\alpha_c = 0.33 \times v_{wind} + 4.5$ Windward: $\alpha_c = 0.16 \times v_{wind} + 4.5$
Shortwave radiation absorptance [-]	System dependent
Long-wave radiation emissivity [-]	System dependent
Interior heat resistance [m^2.K/W]	0.125

The hourly climatic data used for all the simulations were generated with Meteonorm vs.6 (Meteotest 2007), corresponding to a reference year.

Five parameters were selected due to their relevance for undercooling (Barreira et al., 2009) and uncertainty in the selected context:

- Short-wave radiation absortance (exterior rendering) variation between 0.2 (light colour) and 0.7 (maximum value recommended for ETICS (CSTB 1998)).
- Long-wave radiation emissivity (exterior rendering) variation between 0.8 and 0.95 (Kunzel et al. 2002).
- Thickness of the exterior rendering - variation between 0.005 m and 0.02 m (Fleury and Abraham 1982).
- Thickness of the thermal insulation variation between 0.04 m (EOTA (2000) defines this value as a minimum thickness) and 0.10 m (for Portugal this would be the maximum expected thickness).
- Long wave radiation incident on the surface due to the presence of obstacles. The existence of other buildings nearby a façade with ETICS may be simulated by increasing the amount of the atmospheric radiation that reaches the façade, which is a climate parameter (Barreira and Freitas, nd). Therefore, nearby obstacles may change the radiative balance on the surface, by increasing the gains of long-wave radiation during the night. A façade in this situation may be less defaced than a more exposed one as the increase of exterior surface temperature during the night reduces surface condensation. This effect is very important for undercooling and can be introduced in simulation with an increase in atmospheric radiation. That implies a variation in atmospheric radiation increase between 0% and 10%.

METAMODEL

The metamodel was built using design of experiments and regression analysis was performed using SPSS 19.0 software (SPSS inc, Chicago, IL, USA). This software uses the Marquardt-Levenberg algorithm to find the parameters that give the best fit.

There are many types of experimental designs that can be used for this purpose, but the most common ones are the Full Factorial design, 3k, and the Central Composite design, 2k+2k+1. Application of Box-Behnken has reduced the number of runs compared to full factorial experiments. The Box-Behnken experimental design (Box & Behnken, 1960) was employed to investigate the interactive effect of the wall rendering thickness [5mm, 20mm], long-wave radiation emissivity [0.80, 0.95], short-wave radiation absortance [0.2, 0.7] of the exterior layer, the thickness of the thermal insulation [0.04m, 0.10m] and the long wave radiation incident increase on the surface due to the presence of an obstacle [0%, 10%] on CPE. The experimental design consisted of 46 experimental points (with five independent variables and three levels) performed in random order.

The results obtained from Box-Behnken experimental design were analysed by multiple regressions, using the least squares regression methodology, to fit the following second-order equations to all dependent variables.

$$Y = b_0 + \sum_{i=1}^{n} b_i X_i + \sum_{i=1}^{n} \sum_{j=i}^{n} b_{ij} X_i X_j \qquad (2)$$

where Y is the measured response variable, b0, bi and bij are constant regression coefficients and Xi and Xj are the independent variables.

According to the statistical procedure described previously, the second-order polynomial model regression coefficients (Eq. 2) were determined for the walls of each scenario tested response analysis (CPE or N), taking as independent variables: the absorptance (X1), emissivity (X2), thickness of the exterior layer (X3), thermal insulation (X4) of the wall and long wave radiation incident variation (X5). The results revealed a significant regression coefficient ($p<0.05$). As an example, the coefficients for the scenario "North façade with ETICS in Porto" are presented in Table 2.

Table 2
Regression coefficients for the scenario "North façade with ETICS in Porto"

Term	Coefficient - CPE	Coefficient - N
b_0	537,99	68,57
b_1	-623,08	-373,87
b_2	566,66	108,27
b_3	-1520,43	-1439,97
b_4	828,04	731,02
b_5	-210,93	-4,36
b_{11}	144,60	135,83
b_{22}	735,99	351,5
b_{33}	-32,94	-31,0
b_{44}	100,83	94,0
b_{55}	21,72	5,7
b_{12}	-128,27	24,5
b_{13}	-980,87	-928,4
b_{14}	126,33	112,6
b_{15}	107,72	35,15
b_{23}	-1391,10	-1317,23
b_{24}	731,00	652,29
b_{25}	-240,48	-118,16
b_{34}	-67,46	-64,13
b_{35}	48,68	334,89
b_{45}	480,95	-48,77

MONTE CARLO SIMULATIONS

The quantification of CPE and N probability of occurrence was performed in Monte Carlo simulations with the aid of the metamodels described above. The simulation is a sampling process whose goal is to allow observation of the performance of a variable (dependent) due to the behaviour of independent variables that incorporate uncertainty factors. In this paper, the simulation is used to analyse a decision involving risk. The Monte Carlo basic method selects independently random values according to a probability distribution defined. The method of Latin Hypercube randomly selects values in a dependent way. This method divides the distribution intervals with equal probability of occurrence and selects a random value belonging to each range. The Latin Hypercube method is considered a more accurate reproduction of probability distributions chosen for the input variables and hence for the calculation of statistics generated by the simulation, since the range of the distribution is applied more evenly and consistently.

Latin Hypercube was implemented in MATLAB 7.0 to generate samples of 100 combinations of the involved parameters for each Monte Carlo run.

In this phase, all the stochastic parameters were considered to have uniform distributions.

The scenarios for each Monte Carlo run are presented in Table 3.

Table 3
Scenarios for Monte Carlo simulations

Scenario	City	System/Orientation
1	Porto	ETICS/North
2	Porto	ETICS/South
3	Porto	ETICS/West
4	Porto	ETICS/East
5	Porto	Inside insulation/North
6	Faro	ETICS/North
7	Faro	ETICS/South

The results of scenarios 1 to 5 are presented in Figures 3 and 4. The walls with ETICS presented a probability of occurrence of relevant CPE values clearly higher than the comparison case, a wall with inside insulation, indicating an increase in the risk of algae growth. The same conclusion can be extracted using N (number of hours of RH=100%). This corresponds to the expectations as reality has proven that, in Porto, algae growth is more likely to be observed in ETICS façades.

For the behaviour of different façades with ETICS the global trend is correct, as South and East façades usually present much less degradation than North and West façades. Nevertheless, higher differences between façades with different orientations were expected.

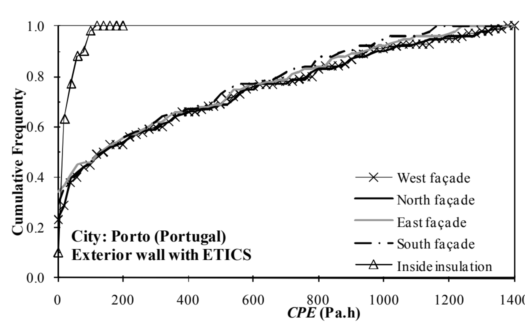

Figure 3 Cumulative distribution of CPE for simulations 1 to 5

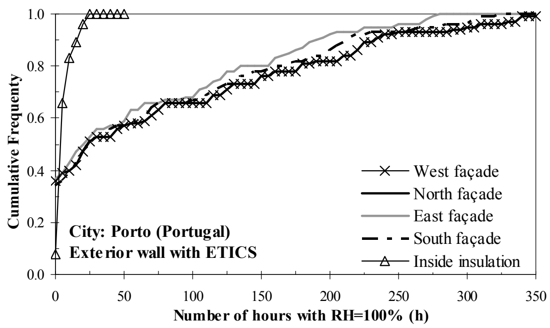

Figure 4 Cumulative distribution of N for simulations 1 to 5

Figures 5 and 6 present the results for ETICS façades, facing North or South in Porto and Faro. Porto is located in the Atlantic coast of Portugal. Faro is located in the South coast of Portugal, benefitting from the influence of the Mediterranean sea and algae growth in ETICS is not usually reported in that region. The results are therefore in line with the expectations as the CPE values are closer to the ones observed for the wall with inside insulation. The N values also respect that trend but present smaller differences.

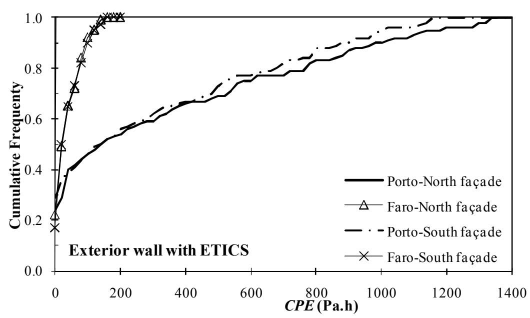

Figure 5 Cumulative distribution of CPE for simulations 1, 2, 6 and 7

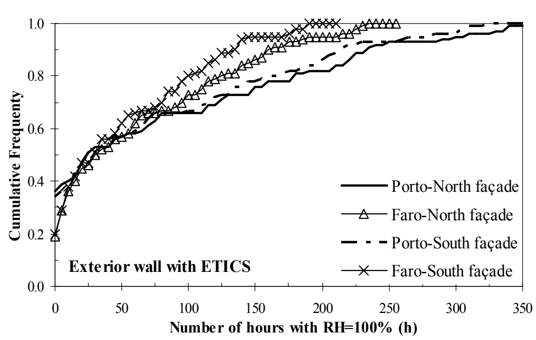

Figure 6 Cumulative distribution of N for simulations 1, 2, 6 and 7

CONCLUSION

The probabilistic risk assessment of ETICS biological degradation was developed in this article, leading to the following conclusions:

- The mechanisms responsible for ETICS defacement were identified in a Fault Tree;
- The Condensation Potential Equivalent (CPE) and the Number of Hours of RH=100% (N) were defined as criteria for risk evaluation;
- Using N would be more adequate as rain effect is included in the analysis, providing a more complete evaluation but, on the other hand, CPE focus the undercooling mechanism, easily correlated with this typical degradation of ETICS;
- The calculation of surface RH is complex and bears uncertainty in itself;
- Only a strategy of scenario comparison can be pursued as no absolute values are available for failure definition;
- The stochastic nature of most of the parameters lead to the application of Monte Carlo simulations, supported by a metamodel to reduce computation time;
- The results provided the expected trends, with cumulative distributions of N and CPE presenting lower values for façades with known lower risk.

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NOMENCLATURE

b_0 = Constant regression coefficients
b_i = Constant regression coefficients
b_{ij} = Constant regression coefficients
CPE = Condensation Potential Equivalent
N = Number of hours with RH=100%
P_{sat} = Water vapor saturation pressure
P_v = Water vapor partial pressure
RH = Relative humidity
T = Temperature
X_i = Independent variables
X_j = Independent variables
Y = Measured response variable

REFERENCES

Barreira, E., Freitas, V. and Ramos, N. 2009. Risk of ETICS defacement - A sensitivity analysis of the demand parameters. Proceedings of the Fourth International Building Physics Conference, pp.543-548. Istanbul, Turkey.

Barreira, E. and Freitas, V. P. nd, The effect of nearby obstacles in surface condensations on External Thermal Insulation Composite Systems

(ETICS) □ Experimental and numerical study□, Journal of Building Physics (accepted for publication).

Box, G.E.P. and Behnken, D.W. 1960. Some New Three-Level Designs for the Study of Quantitative Variables. Technometrics, 2, 455-475.

CENTRE SCIENTIFIQUE ET TECHNIQUE DU BATIMENT □ CSTB (1998) Systèmes d'isolation thermique extérieure avec enduit mince sur polystyrène expansé □ Cahier des prescriptions techniques d'emploi et de mise en oeuvre. Cahier du CSTB 3035. CSTB, Paris, France.

EUROPEAN ORGANISATION FOR TECHNICAL APPROVALS □ EOTA (2000) Guideline for european technical approval of external thermal insulation composite systems with rendering □ ETAG n.º 004. EOTA, Brussels, Belgium.

Fleury, G., Abraham B. 1982. L□isolation thermique des façades par l□extérieur. CSTB, Paris, France.

Kalagasidis, A. & Rode, C. 2011. Annex 55-ST3, framework and case studies. Report for San Antonio meeting.

Häubner, N.; Schumann, R. and Karsten, U. 2006. Aeroterrestrial microalgae growing in biofilms on facades □ Response to temperature and water stress. Microbial Ecology, Vol. 51, 285-293. Springer Science, Berlin, Germany.

Kunzel, H. & Sedlbauer, K. 2001. Biological growth on stucco, Proc. Perform. of Exterior Envelopes of Whole Buildings VIII: Integration of Building Envelopes. Florida: ASHRAE.

Kunzel, H., Schmidt, Th. & Holm, A. 2002. Exterior surface temperature of different wall constructions □ Comparison of numerical simulation and experiment, Proc. 11th Symposium of Building Physics Vol. 1: 441-449. Dresden.

Lengsfeld, K., Krus, M. 2004. Microorganisms on facades □ Reasons, consequences and measures, IEA □ Annex 41 □Moist-Eng□ Meeting. IEA, Glasgow, UK.

Meteotest 2007. Meteonorm □ Version 6.0. Meteotest, Bern, Switzerland.

Pallin, S., Johansson, P., & Hagentoft, C.E. 2011. Stochastic modeling of moisture supply in dwellings based on moisture production and moisture buffering capacity. IBPSA □ Building simulation 2011.

Pallin, S. 2012. Probabilistic risk assessment of energy efficient retrofitting techniques □ focus on multi-family dwellings and the effects of changing air movements. Thesis for the degree of licenciate of engineering. Department of civil and environmental engineering. Chalmers university of technology. Gotheburg, Sweden.

Pietrzyk, K. & Hagentoft, C. 2008. Reliability analysis in building physics design, Building and Environment 43 [4]: 558-568.

Venzmer, H. 2001. Grüne Fassaden nach der instandsetzung durch WDVS? Nicht bestellt und dennoch frei Haus (Green facades after renovation with ETICS? Not ordered but delivered freely). 3. Dahlberg-Kolloquium.

Zhao, J., Plagge, R., Nicolai, A., Grunewald, J. & Zhang, J., 2011. Stochastic study of hygrothermal performance of a wall assembly □ the influence of material properties and boundary conditions. HVAC&R Research, 17(4):591□601.

Zheng, R., Janssens, A., Carmeliet, J., Bogaerts, W. & Hens, H. 2004. An evaluation of highly insulated cold zinc roofs in a moderate humid region □ part I: Hygrothermal performance, Construction and Building Materials 18 [1]: 49-59.