SENSITIVITY ANALYSIS OF AN ENERGYPLUS SIMULATION MODEL OF THE AMBIENT HUMIDITY IN AN OLD BUILDING

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ABSTRACT

In France, old buildings (built before 1948) represent 10 millions of dwellings and have to be retrofitted. However, the presence of the moisture in old buildings may be problematic for retrofitting solutions. Indeed, those may accentuate surface condensation and cause moulds, degrade the structure or reduce the comfort. That is why it is essential to predict hygrothermal behaviour of these buildings.

A sensitivity analysis is performed to know the sensitivity of ambient moisture to input data. EnergyPlus with heat and moisture transfer algorithm is used for this analysis. Two categories of parameters significantly affect ambient moisture: infiltrations that cause 20% of influence and hygrothermal properties of materials (mainly thickness and diffusion resistance factor). The influence of materials depends on their proportions in the building.

NOMENCLATURE

X_z = variable X for the zone
X^t = variable X at time t
W = specific humidity (kg_{water}/kg_{dryair})
$kg_{mass_{sched\ load}}$ = internal latent loads (kg_{air}/s)
A_i = area of element I (m²)
h_{mi} = inside moisture transfer coefficient of element I (kg/m².s)
$\dot{m_i}$ = mass airflow from zone i (kg_{air}/s)
$\dot{m_{inf}}$ = mass airflow from outdoor (kg_{air}/s)
$\dot{m_{syst}}$ = mass airflow from humidistat (kg_{air}/s)
W_{surfsi}= specific humidity of surface (kg_{water}/kg_{dryair})
$\widehat{HS}_0$ = average on the year of specific humidity for the base case (kg_{water}/kg_{dryair})
$\widehat{HS_i}$ = average on the year of specific humidity for the case i (kg_{water}/kg_{dryair})
$HS_0(t)$ = specific humidty at time t for the base case (kg_{water}/kg_{dryair})
$HS_i(t)$ = specific humidty at time t for the case i (kg_{water}/kg_{dryair})

INTRODUCTION

The current energetic and environmental constraints require the improvement of the energy performance and environmental quality of building. Indeed, the building sector represents about 40% of the world energy consumption (AIE, 2010).

Energy performance is not the same for the whole housing stock. In France, three main periods characterize the entire housing stock. The first part, which represents about 10 millions of dwellings, was constructed before 1948 (Cantin et al., 2010). It is distinguished by a social and cultural heritage. The industrialized buildings submitted to economic and profitability constraints compose the second part of the housing stock. The last part represents the new buildings that respect the thermal regulation since 1975.

For the old buildings, the average energy consumption is below 227 kWh/m² per year (Cantin et al., 2010). Therefore, in this energetic context, most of the existing buildings have to be refurbished. The old buildings represent a large potential for energy savings but retrofitting measures do not always deliver the acceptable functional performance and energy consumption required.

Unlike new buildings, old dwellings are not waterproof and indoor ambient moisture is strongly dependant on outdoor moisture (Cantin et al., 2010). So, the presence of moisture may be problematic for retrofitting solutions. Indeed, the indoor insulation of walls may decrease the exterior surface temperature which can be below dew-point temperature (Aelenei et al., 2008). Moreover, retrofitting measures may affect air change rate so therefore indoor moisture. Aelenei et al., 2008 shows that condensation depends on the surface energy balance and on the moisture content of the ambient air. Therefore, retrofitting solutions may accentuate condensation risk and cause moulds or degrade the structure (Moradias et al., 2012).

In this context, the building simulation tools can be very helpful to propose adapted retrofitting measures. Usually, the indicators to identify retrofitting solutions are energy consumption and temperature for summer comfort. To prevent from some humidity damages and to be efficient in proposed refurbishment solutions, it is important to know the ambient moisture. Retrofitting measures affect input data of simulation. So, it is important to know the sensitivity of the moisture model to input data. Knowing sensitivity of ambient moisture to these data gives information about solutions and help decisions. However, the moisture model in most simulation tools is simple.

The aim of this paper is to determine the most influent parameters on indoor ambient moisture in simulation. The determination of these parameters helps to perform more efficient energetic audits and monitoring in the first part and to give information about the impact of retrofitting measures in the second part.

This work begins by a literature review about hygrothermal models and the choice of a used model: EnergyPlus with HAMT Algortihm. Then, a comparison of the selected wall heat and moisture model transfers and WUFI 2D is presented on a simple case.

Finally, a sensitivity analysis is performed on a reference building to determine influent parameters on ambient moisture.

LITTERATURE REVIEW

Most thermal building simulation codes, for example TRNSYS and EnergyPlus, focus on prediction of temperature fields and energy demand. Therefore, the moisture exchange with materials is simplified (Jansens et al., 2005). However, old buildings are very sensitive to moisture. This parameter must be taken into account in simulation. But, the aim is to consider engineering models to help actors of retrofitting solutions.

EnergyPlus developed a new transfer algorithm: Heat And Moisture Transfer (HAMT) which takes into account moisture transport (liquid and vapour) in the wall and the effect of moisture on hygrothermal properties (EERE, 2011).

The algorithm is based on the equations developed by Künzel (Künzel et al., 1995). This model treats only one dimensional hygrothermal transfer. The movement and storage of heat and moisture from exterior and interior surfaces are represented by a finite element model.

Finally the specific humidity of indoor climate is based on Equation (1) (EERE, 2011).

$$\rho_{air} V_z C_w \frac{dW_z}{dt} = \sum_{i=1}^{N_{sl}} kg_{mass_{sched\,load}} + \sum_{i=1}^{N_{surfaces}} A_i h_{mi} \rho_{air,z} (W_{surfs_i} - W_z^t) + \sum_{i=1}^{N_{zones}} \dot{m}_i (W_{zi} - W_z^t) + \dot{m}_{inf} (W_\infty - W_z^t) + \dot{m}_{sys} (W_{sup} - W_z^t) \tag{1}$$

The transient air mass balance equation for the change in the zone humidity ratio is equal to the sum of internal scheduled latent loads, the infiltrations, the system, the multizone airflows and the convection to the zone surfaces.

Therefore, ambient specific humidity is affected by the HAMT algorithm because of moisture on the surface (the second term of Equation (1)).

Before pursuing the study, a comparison between a validated model for moisture and thermal transfer in the wall and EnergyPlus is carried out.

COMPARISON OF HAMT ALGORITHM OF ENERGYPLUS AND WUFI 2D

To realize a simple evaluation of the EnergyPlus HAMT algorithm, WUFI 2D is used to compare results. WUFI's model is built with differential equations for heat and moisture transport developed by Künzel, (Künzel et al., 1995) as was HAMT for EnergyPlus. This model was validated by the benchmark test of EN 15026 (WUFI, 2012) and experimental data (Oustad et al., 2005 and Holms et al., 2002).

The construction of the comparison method is based on benchmark No. 2 for one dimensional case of the HAMT model presented by Hagentoft et al., 2004. The conditions are the same as the analytical case as presented in Table 1.

Table 1

Conditions of evaluation case

	Outdoor	Indoor
Air temperature (°C)	20	20
Relative humidity (%)	45	65

There is no radiation, rain and wind. The boundary conditions are the same for both the EnergyPlus and WUFI 2D models.

The layer is initially in moisture balance with the ambient air, which has a constant temperature of 20°C and a constant relative humidity of 95%.

The two models don't concern the same scale: EnergyPlus treats a zone and WUFI concerns a wall. However, we only interest in the evolution of the water content of the wall for the both models. A specific case is built with EnergyPlus.

One zone is constructed with EnergyPlus (2x2x2m^3). Five surfaces are adiabatic and they don't consider moisture transport. The last surface is an outdoor wall; its thickness is 0.2 m.

Two materials from the WUFI database are tested: Tuff and Concrete. Table 2 presents the basic values of the materials.

The temporal evolution of water content in the wall for the two models is analyzed. In this paper, results about Tuff are presented. Results for the Concrete are similar.

Table 2

Properties of Tuff and Concrete from WUFI Database

Properties	Tuff	Concrete
Bulk density (kg/m^3)	1450	600
Porosity (m^3/m^3)	0.45	0.77
Specific heat capacity (J/kg.K)	925	850
Thermal conductivity (W/m.K)	0.338	0.12
Water vapour diffusion resistance (-)	10	16

Results of water content in the wall are compared during one year. Figure 1 presents the evolution of water content in the wall for the two algorithms during a year.

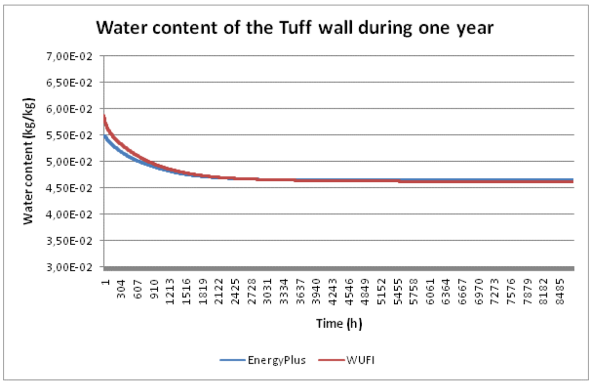

Figure 1 Evolution of water content in a Tuff wall with EnergyPlus and WUFI algorithms

The correlation between the two models is important ($WC_{EnergyPlus} = 1.312 WC_{WUFI} - 0.14$ avec $R^2=0.998$) and the differences are low. Indeed, the director coefficient of the equation is close to 1. However, there are some points which underline more variations. The beginning of the curve underlines various behaviours. Three or four days are needed to stabilize indoor relative humidity at 65% for EnergyPlus. This time may explain differences between the two codes at the start of the simulation. Moreover, final water content is the same for the both models. Since we study old walls, it is possible to launch simulation for two years to balance initial conditions in the wall.

The behaviour of water content in the wall is similar for the two models. The EnergyPlus HAMT algortihme gives consistent results for the water content of the wall and will be used for this study.

SENSITIVITY ANALYSIS

Methodology

The aim of a sensitivity analysis is to determine the change in model output data that results from little variation in model input data (Loucks et al., 2005).

Unlike an uncertainty analysis, a sensitivity analysis studies a localized region of the space of inputs. This region is around the values that are supposed to be true.

This paper is the first part of a global work on uncertainty of old buildings modelling. We examine the effects of change on one parameter. Therefore, we neglect the interactions between input parameters.

The importance of different input parameters will depend on output criteria and the scale of consideration. In our case, the studied output is the indoor ambient specific humidity. Relative humidity was ruled out because it strongly depends on temperature.

We study the variation of specific humidity for each zone of the building.

The hygrothermal model input data can be classified into four categories:

- geometrical building data,
- hygrothermal characteristics of materials: thickness, thermal conductivity, initial moisture content, sorption, suction, diffusion, etc.,
- weather data: exterior relative humidity, temperature and radiation,
- occupancy data: interior ambient temperature, internal gains, air change rate,

Equation (1) and the in-situ observations led to the first selection of input data. One hundred and three (103) parameters were selected. We don't consider the geometrical building data in this study.

The perturbation of each parameter is 5%. The 104 simulations (base case and variants) were carried out thanks to coupling EnergyPlus and Matlab®.

We are interested in the annual variation of specific humidity. We adapt the energy consumption indicators of the ASHRAE guideline 14*2002 to specific humidity. The selected indicators to analyse the effect of each parameter are both mean bias difference and coefficient variation of difference.

- Mean bias difference (MD):

$$MD_i = (\widehat{HS}_0 - \widehat{HS}_i)/\widehat{HS}_0 \qquad (2)$$

- Coefficient variation of difference (CVD):

$$CVD_i = \frac{1}{8760}\sum_t |HS_0(t) - HS_i(t)|/\widehat{HS}_0 \qquad (3)$$

The base simulation is the simulation with value supposed to be true (number 0). These two indicators will identify the individual effect of the perturbation of each factor.

If the value of the mean bias difference is positive, the increasing of the value of the parameter decreases the output average. If the value of the mean bias difference is negative, the increasing of the parameter increases the output average.

Case study

Old buildings are constructed with traditional techniques and local materials. Therefore, those buildings depend on the size, the local architectural style of construction and the material available on site. However, most of them were built with stone. Among the diversity of existing stones, limestone represents 10% of the total sedimentary stock. It is widely used for constructions in France (Stéphan et al., 2012). This paper is focused on a highly porous limestone because of its hygrothermal properties and moisture problematic.

A highly porous limestone

"Tuffeau" is a limestone found in the Loire Valley in France. Its porosity is important and varies from 35 to 45%. This value explains the low value of its density from 1.20 to 1.65 (Beck, 2007).

This stone's content may contain a large proportion of moisture up to a maximum of 35% of its mass.

It is a hygroscopic material and its hygrothermal properties vary as a function of its moisture content. For example, the transformation from a dry state to a saturated one doubles its thermal conductivity (Stéphan et al., 2012). Table 3 presents the main properties of Tuffeau stone.

Table 3

Main properties of Tuffeau stone

Properties	Value
Porosity	0.40
Density	1400 kg/m^3
Specific Heat	1000 J/kg.K
Thermal conductivity (dry)	0,4 W/m.K

Moisture is the first cause of degradation of Tuffeau stone (Dessandier, 2000). It affects the rocks physically, chemically and biologically. The observed alterations on Tuffeau may decrease mechanical structure and thermal resistance. Figure 2 presents an example of common alterations. These alterations reduce the thickness of the wall. Therefore they cause structural problems and thermal bridges.

Figure 2 Disaggregation of Tuffeau stone (left) and split-up of thin plates of Tuffeau stone (right).

That's why it is essential to predict hygrothermal behaviour of Tuffeau buildings.

Presentation of the dwelling

A rural old house (16th century) in the Loire Valley, France is selected as a reference building to perform the calculation and the sensitivity analyses. This case study is considered an example of a common rural old house built with Tuffeau representing common building materials and construction techniques of this type of architecture. This dwelling is about 200 m². Six zones compose the building: kitchen, living room, bedroom, bathroom, attic spaces and barn.

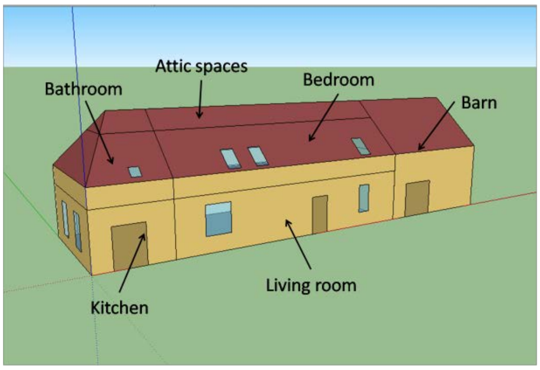

Figure 3 Schema of the case of the study

Figure 3 represents a view of the house. The building is oriented towards the South/North. The thickness of the walls is 0.50 m. The roof of the second floor is insulated with glass fiber. Windows are simple glass.

The ventilation is natural and there is not any cooling system. Barn and attic spaces are not insulated. They benefit from a great number of infiltrations.

Simulation

The case of study is simulated with EnergyPlus v7.2.0. The timestep is 2 minutes for the HAMT algorithm but the frequency of output report is one hour. The model is created thanks to the plug-in of Sketchup®.

The properties of material are based on measures of K. Beck (Beck, 2007) and the library of moisture materials of EnergyPlus (EERE, 2011). Table 4 presents the materials and their thickness.

The calculation uses the climate of Angers (France).

The natural ventilation is modelling thanks to infiltrations in every room. The infiltration rate takes into account the equivalent leakage area, the effect of the wind and the effect of indoor/outdoor temperature differences (Equation (4)).

$$Inf = \frac{A_L}{1000}\sqrt{C_s \Delta T + C_w (WindSpeed)^2} \qquad (4)$$

The occupation is simulated by internal gains of 4 W/m² in kitchen, living room, bedroom and bathroom. The schedule is the one of French thermal regulation of 2005 (CSTB, 2006). The ambient indoor temperature is fixed by the French thermal regulation: 19°C during occupancy and 16°C during the unoccupancy or during the night.

Table 4
Constructions details

Construction	Materials	Thickness (cm)
Window	Clear glass	0.3
First floor	Tiling	5
Roof	Slate	3
Second floor	Wood Glass fiber BA13	5 10 1.3
Intermediate floor	Wood Air BA13	5 5 1.3
Insulated roof	Slate Air Glass fiber BA13	3 5 10 1.3

RESULTS AND DISCUSSION

The simulations for the 103 parameters are launched and for each one, we calculate the two indicators MD and CVD. To complete these two indicators, we calculate the percentage of influence of each parameter in front of the total influence (Equation (5)).

$$P_i = \frac{|MD_i|}{\sum_i |MD_i|} \tag{5}$$

Then, we add this percentage of influence by ranking of parameters to get a curve of influence. We select the parameters that are responsible for 90% of the total influence in each zone. Figure 4 presents the curve of influence for the living room.

Table 5 describes the selected parameters.

Only about 15% of parameters cause 90% of influence in each room. Throughout the rest of the paper, we will only study the parameters in Table 5.

Table 5 highlights similarities between the zones and some differences. We will begin studying the common features then we will analyze the differences.

The most influent parameter on specific humidity in each room is infiltration rate. Indeed, the equivalent leakage area is the main parameter in all the rooms. Its percentage of influence is about 20% in each room. So only this parameter is responsible for one fifth of the total influence. Moreover, the two infiltrations coefficients (stack-induced coefficient and wind-induced coefficient), that are used in the calculation of infiltration rate (Equation (4)), are selected too.

This analyse is consistent with Equation (1). Its fourth term represents the infiltration rate and outdoor specific humidity. These three parameters are directly used in the calculation of infiltration mass flow.

The material properties are influent parameters on specific humidity of indoor ambiance. Two main characteristics are influent: the thickness and the vapour diffusion resistance factor.

The thickness affects heat and moisture transfers. Moreover, it determines heat and moisture storage capacities in the material. Spatial repartition of water content depends on the thickness of the wall. Therefore, the thickness affects the moisture quantity that may transfer from the wall to the room.

The vapour diffusion resistance factor characterizes the material capacity to let vapour transfer. The quantity of vapour that crosses the wall and enters, increases as the diffusion resistance factor decreases.

For the predominant material in this building, the Tuffeau, more properties are observed as the liquid transport factor by redistribution. This coefficient characterizes the liquid transfer in the material. As a diffusion resistance factor, this parameter affects the moisture proportion that crosses the wall and appears on the surface.

Specific humidity in each room is influenced by set point temperature. It is used in the calculation of infiltration rate (Equation (4)). Moreover, indoor temperature determines the maximal quantity of moisture in the air. Finally, it is a drive force of heat transfers. Even if set point temperature is used only during winter, it affects some level of specific humidity.

Now, we will study the differences between the rooms.

A classification of the zone is possible. Influent parameters are similar between the kitchen and the living room (first floor) and between the bedroom and the bathroom (second floor).

Figure 5 presents the MD for the two rooms of the first floor for the 14 main parameters of the kitchen. The ranking of the parameters for the living room is a little different. Set point temperature is more influent in the living room than in the kitchen. Figure 5 underlines that the influence of parameters are higher in the living room than in the kitchen. The larger surface in the living room may explain this phenomenon.

The influent materials are Tuffeau and BA13. Tuffeau is the predominant material in these two rooms. BA13 is the inside layer of celing. So these materials interact directly with the indoor air of the rooms.

Finally, convection coefficients affect specific humidity of these two rooms. They are used in Equation (1) and affect the air movements between surfaces and ambiance.

The mean bias difference characterizes a global behaviour because it deals with the average during the year. The second indicator deals with dynamic behaviour of specific humidity. The ranking of the parameters is different if we consider the mean bias difference or the CVD. For example, Table 6 presents the ranking for MD and CVD in the living room.

Table 6

Ranking of the parameters for MD and CVD indicators in the living room

	MD	**CVD**
1	Equivalent leakage area	Set point temperature
2	Set point temperature	Equivalent leakage area
3	Tuffeau thickness	Tuffeau thickness
4	BA13 thickness	BA13 thickness
5	BA13 diffusion resistance	BA13 diffusion resistance
6	Wind infiltration coefficient	Wind infiltration coefficient
7	Air thickness	Air thickness
8	Stack infiltration coefficient	BA13 thermal absorption
9	Tuffeau redistribution factor	Tuffeau sorption
10	Tuffeau diffusion resistance	Stack infiltration coefficient

There are not the same parameters in the two rankings. Set point temperature is the most influent parameter for the CVD and ranks second for the MD. For the on-the-year average, the set point temperature is considered only in the winter. So, its influence is mitigated contrary to the CVD.

Moreover, some new parameters appears in the ranking for the CVD : Tuffeau sorption for example. It characterizes the water content in the wall as a function of relative humidity of the ambiance.

The sensitive parameters are different if the objective is the average during the year or the dynamic behaviour.

For the second floor, the observed differences are the materials that affect the specific humidity. Indeed, contrary to the first floor, the most influent material is the glass fiber (it is the Tuffeau for the first floor).

Glass fiber insulates the roof so there is not glass fiber in the first floor. Tuffeau affects specific humidity of the second floor but the value is lower than for the first floor. The proportion of Tuffeau in the second floor is lower than in the second floor.

This analysis underlines that influence of the materials depends on their proportions in the building.

CONCLUSION

The first aim of this study is to improve the old building modelling. The problematic of moisture is important for these buildings.

EnergyPlus moisture model takes into account wall transfer and wall storage. Therefore, it is an improvement for moisture consideration. However, in this first study, we do not introduce moisture sources, so we neglect a parameter that seems important for specific humidity.

Two categories of parameters are underlined: infiltrations and hygrothermal properties of materials. Infiltrations cause 20% of the total influence.

Retrofitting significantly affects these parameters. Infiltrations are modified by the windows being changed and new materials insulate the walls. So, this first analysis highlights the effect of a retrofitting on the building performance and the uncertainty of this effect.

Indeed, a solution can improve a building for some parameter values but it turns in bad performances with other values. The future aim is to evaluate the pertinence of a solution in regards to the uncertainty of input parameters.

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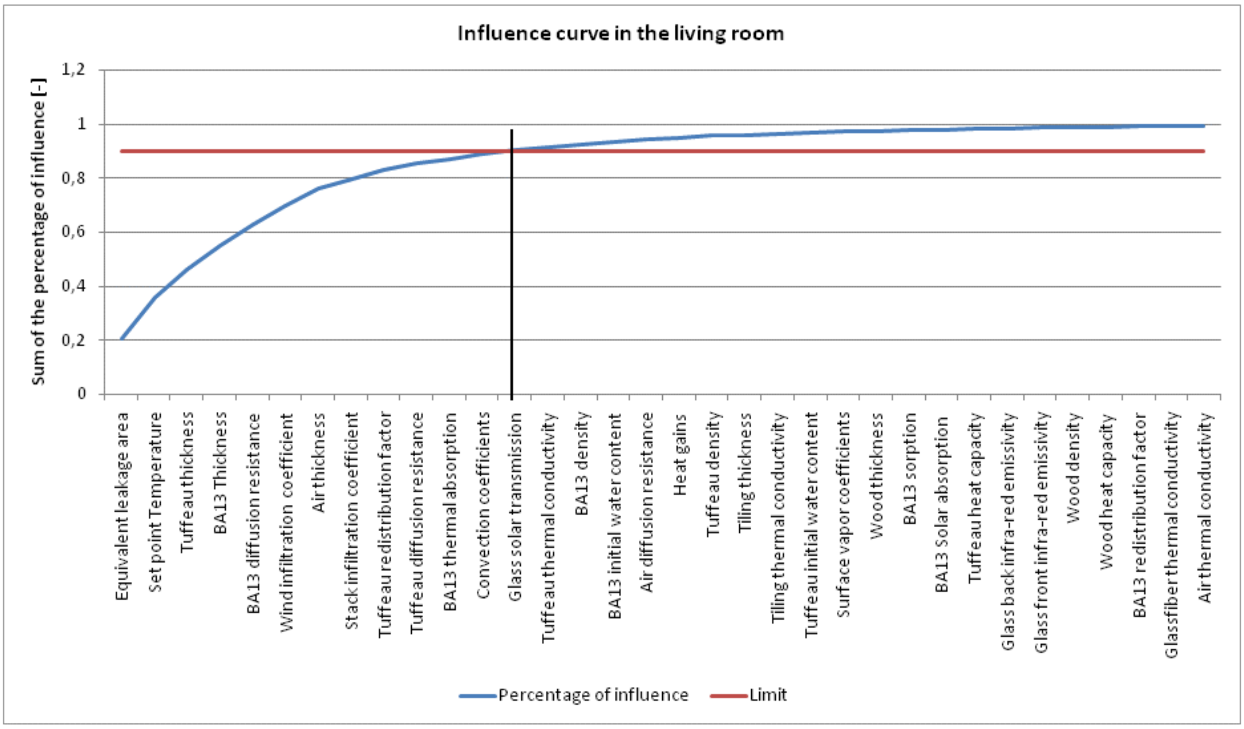

Figure 4 Influence curve for MD indicator in the living room and the limits of 90% of influence

Table 5a
Color legend of Table 5

Color	Parameters categories
▓	Infiltrations
▒	Occupancy
░	Convection
	Materials properties

Table 5b
Ranking of the parameters responsible of 90% of influence in each room

Bedroom	**Bathroom**	**Living room**	**Kitchen**
Equivalent leakage area	Equivalent leakage area	Equivalent leakage area	Equivalent leakage area
Glassfiber thickness	Glassfiber thickness	Set point temperature	Tuffeau thickness
Glassfiber diffusion resistance	Tuffeau thickness	Tuffeau thickness	BA13 thickness
BA13 thickness	Glassfiber diffusion resistance	BA13 thickness	BA13 diffusion resistance
BA13 diffusion resistance	BA13 thickness	BA13 diffusion resistance	Set point temperature
Wind infiltration coefficient	Wind infiltration coefficient	Wind infiltration coefficient	Wind infiltration coefficient
Tuffeau thickness	BA13 diffusion resistance	Air thickness	Air thickness
Air thickness	Set point temperature	Stack infiltration coefficient	Stack infiltration coefficient
Stack infiltration coefficient	Air thickness	Tuffeau redistribution factor	Tuffeau redistribution factor
Set point temperature	Stack infiltration coefficient	Tuffeau diffusion resistance	Tuffeau diffusion resistance
Glass solar transmission	Tuffeau redistribution factor	BA13 thermal absorption	Convection coefficient
Tuffeau redistribution factor	Tuffeau diffusion resistance	Convection coefficient	Tuffeau sorption
Tuffeau diffusion resistance	Glass solar transmission	Glass solar transmission	Tuffeau thermal conductivity
Slate thickness	Slate thickness		Glass solar transmission
Tuffeau thermal conductivity	Tuffeau thermal conductivity		
Wood sorption	Slate diffusion resistance		
Slate diffusion resistance			

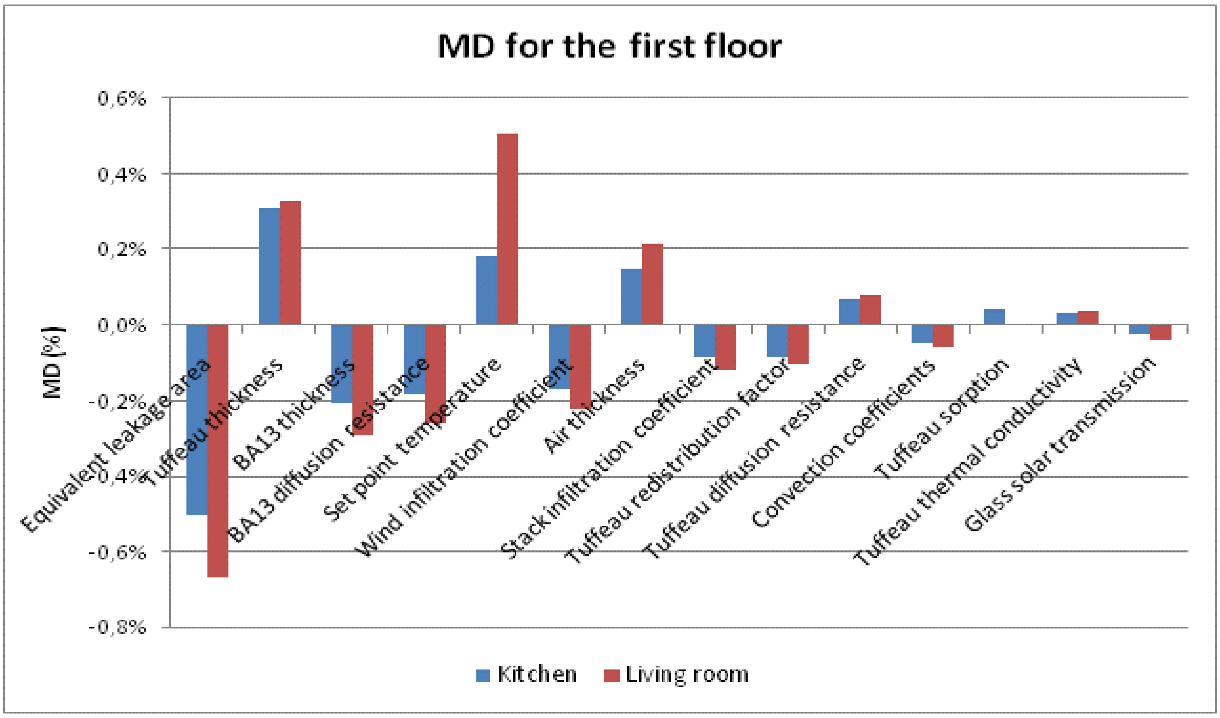

Figure 5 MD indicator for the living room and the kitchen for the 14 first parameters