Journal of Construction in Developing Countries

Manuscript Title	Reduce Mould Risk during the Building Design Stage: Case Studies in Southeast China
Authors	Shenghuan Zhao and Enrico De Angelis
Submitted Date	30-May-2018 (1st Submission)
Accepted Date	06-Nov-2018

Reduce Mould Risk during the Building Design Stage: Case Studies in Southeast China

Abstract

Indoor mould is usually discussed for the building operation phase rather than the design stage. Moreover, the majority of existing studies were conducted by mechanical engineers rather than architects, who typically have a broader view of the whole project. The purpose of this paper is to obtain a quantitative mould risk scenario across the Yangtze River Delta in China and make a matrix including all the possible design chances to reduce the mould risk. A series of software is utilized to simulate the mould risk in three main cities across that region. Simulation results confirm high mould risk in all selected cities and the mould growth rates in different orientations match the Wind-Driven-Rain diagram. After the simulation, all factors that can be tuned for the mould prevention were analysed. Authors found that only humidity and substrate (material of finishing layer) characteristics can be practically controlled for the mould avoidance. Meanwhile, the Development Design Stage is the essential design phase while the envelope is the most crucial building element for mould prevention.

Keywords

Moisture, Building envelope, Building science, Building design, Building pathology

1. Introduction

Due to its negative effect on occupants' health (Nunez & Hammer, 2014, H. Moon & Augenbroe, 2004), the indoor mould problem has received much attention from governments in many developed countries (ASHRAE, 2012, U.S. Environmental Protection Agency, 2012, U.S. Environmental Protection Agency, 2013). Nevertheless, there is no code in China specifically mentioning or offering instructions on indoor mould prevention. Even design codes for hospitals and schools, which actually should require a higher indoor air quality, states nothing on this issue. All of this does not mean mould-free in China. The Yangtze River Delta (black colour filled in Figure 1), including Shanghai municipality and two nearby provinces, is known as the most mould-vulnerable place in the country. A survey (Wei, 2016) indicated that more than half of the investigated families in Shanghai had the indoor mould problem. The primary cause may be the rainy season called Plum Rain Season from June to July each year. Everything during that period becomes extremely mould-vulnerable because of the highest annual temperature and humidity. Meanwhile, the fruit plums, sharing the same pronunciation of mould in Chinese, ripen and fall down from trees like a plum rain. Ancient habitants replaced the word mould with plum to make that period not so annoying but a little bit poetic (Baike, 2016).

It is time and money consuming to remediate a wall after the mould appearance (H. Moon & Augenbroe, 2004). Moreover, many building design decisions influencing indoor air quality (IAQ) are hard to be revised after the early design stage (ASHREA, 2009). Therefore, the mould risk should be proactively considered since the design starts. Nevertheless, the majority of related studies are done by mechanical engineers who only focused on the HVAC system without considering all the design chances. The correlation between building design and the mould risk is rarely discussed in the literature. It means that there are more ignored design opportunities can be utilized for the mould prevention.

The present paper tries to diagnose the wall mould-vulnerability by computational simulation: 1) hygrothermal condition (moisture and temperature) on the wall inner surface will be simulated first; 2) the water content in spores will be calculated according to the previous simulation; 3) the mould growth rate and mould index will be computed based on the spore situation. Afterwards, all the design strategies for mould-prevention are scrutinized, and integrated along the design workflow. In the end, a matrix identifying possible design chances for the mould prevention is presented. Due to the complexity of the building as a system, the current study is impractical to be validated by on-site experiments. However, this investigation still has noteworthiness with its effort on connecting the building science with architects. It could be beneficial to architects who frequently ignore or have no idea how to consider the indoor mould problem, and it is also useful for policymakers to make more scientific design guides.

2. Mould risk diagnosing

2.1. Selected cities and their climates

Three main cities (Figure 1) across the Yangtze River Delta are observed locations: Hangzhou (capital of Zhejiang provenience), Shanghai (special municipality) and Nanjing (capital of Jiangsu provenience). Three cities are all located in the hot summer-cold winter climate zone (Figure 1) in the official definition and share similar climates (Table 1). The most distinctive meteorology aspect is the Annual Wind-Driven Rain: Hangzhou has the most rain from the southeast, Shanghai maximizes the rain gain in 22.5 degrees east of south, while Nanjing obtains the majority rain in the south. Other geology and climate information like temperature also can be found in Table 1.

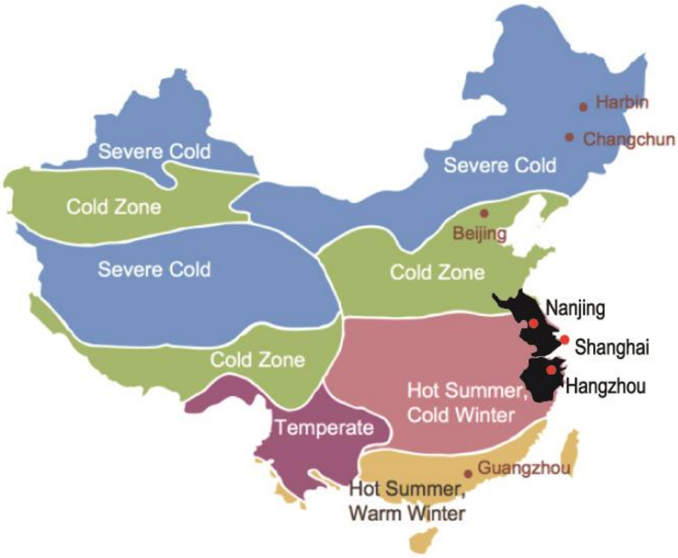
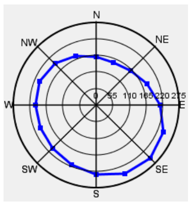
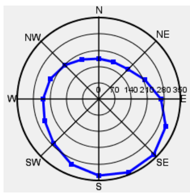
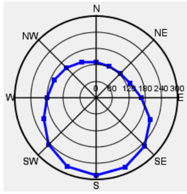


Figure1. Location and climate zone information of three cities, elaborated by the author.

Table 1: Detailed climate information of three cities

Site	**Position** (Lat, Long, h a.m.s.l)	**Air Temp.** (min, mean, max), (℃)	**RH** (%) (min, mean, max)	**Irradia-tion** (kWh m^{-2} y^{-1})	**Mean wind speed** (m s^{-1})	**Rain-fall** (mm y^{-1})	**Wind-Driven Rain sum** (mm y^{-1})
Hang-zhou	30.23 N, 120.17 E, 43 m	-3, 17.6, 40	27, 70.5, 100	3122.3	2.3	1361.6	
Shang hai	31.17 N, 121.43 E, 7 m	-3.9 ; 17.5 ; 36.6	29, 69.1 ; 100	3085.7	3.5	1313.7	

Nanjing	32 N, 118.80 E, 12 m	-7, 36.9	16.4,	22, 72.3, 100	3057.6	2.6	1172.6	

2.2. Wall structures selected for simulation

To reduce energy consumption in the building sector, the central and local governments published a series of atlases on energy-efficient wall compositions. Wall types investigated herein are all from these official atlases (listed in the second row of Table 2). Hangzhou and Nanjing have their own local atlases while the one used for Shanghai is a national one. The one Zhejiang proposed is self-insulation typology while the other two provinces have individual insulation layers. Property indices of core materials (layer 4 for Hangzhou, layer 6 for Shanghai and Nanjing) are stated in those atlases. However, Layer 1 to layer 3 in Table 2 are not included in any atlas but the most common internal-surface composition across the Yangtze River Delta. Materials not found in official recommendations are replaced by similar things from the WUFI® software database (Table 3).

Table 2: Sources and composition of three multi-layer walls (from internal to external)

	Hangzhou		**Shanghai**		**Nanjing**	
	Integral Structure and Energy Saving of Lightweight Concrete Block Wall		Atlas of the assembled monolithic residential structures		External insulation system with HR decorative insulation board	
	Names of materials	Thickness (mm)	Names of materials	Thickness (mm)	Names of materials	Thickness (mm)
1	Latex painting	3	Latex painting	3	Latex painting	3
2	Gypsum plaster	8	Gypsum plaster	8	Gypsum plaster	8
3	Mixed mortar	20	Mixed mortar	20	Mixed mortar	20
4	Lightweight concrete	240	Concrete	190	Concrete	190

	blocks (HQLCB240950)		blocks (2 rows of holes)		blocks (2 rows of holes)	
5	Cement mortar	20	Cement mortar	20	Cement mortar	20
6	Gypsum plaster	8	EPS insulation panel	90	HR decorated insulation panel	30
7	Facial brick	12	Facial brick	12	N/A	N/A
	Total thickness	311	Total thickness	343	Total thickness	271
	U value	0.896	U value	0.199	U value	0.166

Table 3: Properties of three (Self-) insulation materials and the external coating layer

	Density (kg/m³)	Conductivity (W/mk)	Water vapour resistance factors	Typical Built-in Moisture (kg/m³)	Specific heat capacity (J/kg•K)
Lightweight concrete blocks (HQLCB240950)	1250	0.27	80*	200*	850*
EPS insulation panel	18	0.041	30	0.13	1500
HR decorated insulation panel	20	0.03	3.4*	4.5*	850*
Facial brick	3000	0.6	9.5*	30*	850*

** Values from similar products in the WUFI® database*

2.3. Software introduction and boundary settings

2.3.1. Meteonorm and WUFI®

The broadly used climate data format EPW does not contain the rain data, which is crucial for the mould risk simulation. Therefore, climate datasets used herein are from software Meteonorm. Although data from Meteonorm is not measured on-site but converted from surrounding statistics, it has been validated very close to the reality (Häglund, Isaksson, & Thelandersson, 2010). For settings in the Meteonorm, radiation period is from the year 1991 to the year 2010 while the base temperature is from years 2000 to 2009. These two options are closet to the current date. IPCC Scenario for future periods is picked with the B1 mode, which hypothesizes a rapid economic growth and stable economic, social and environmental situation.

A set of WUFI® software, which has been validated by various of experimental examinations (Sedlbauer, 2001a), is used for the mould risk prediction. The whole simulation includes two steps (Figure 2): WUFI® Pro simulates the hygrothermal condition, then the water content of spores and the associated mould risk are calculated by WUFI® BIO. The latest software WUFI® VTT which has the similar function as WUFI® BIO is also used for the mould index prediction parallelly.

Figure 2. Software architecture for the simulation process

Hygrothermal calculation models of simulation software can be categorized as 'envelope models' and 'models within a whole building simulation' (H. J. Moon & Augenbroe, 2003). The first kind of models is unable to consider dynamical sources like HVAC system, internal latent loads like heat radiance from occupants, nor transient hygro-thermal behaviour. For this reason, they offer less realistic results than the second category models which take into account sources like the HVAC system (H. J. Moon & Augenbroe, 2003). Belonging to the first category, the numerical model in software WUFI® *Pro* only assumes a steady state thermal environment. The simulated position is the other drawback. WUFI® Pro only can monitor the wall surface rather than the joint places between wall and wall, wall and window, which are more mould vulnerable due to the thermal bridge.

For the mould risk prediction models, there are more options beside the WUFI® VTT and WUFI® BIO. More specific information regarding to calculation models can be found in the review made by Vereecken & Roels (2012). Current authors select these two models because of the free access to these software. The main difference between them is that WUFI® VTT considers the growth diminish after longer dry periods while WUFI® BIO does not (FRAUNHOFER BUILDING INNOVATION, 2017). Meanwhile, results from both software only identify the situation on the wall inner surface, which is another limitation of the present study.

2.3.2. Boundary settings

A six-storey building (around 18m) with common residential typology, is hypothesized for this simulation. Building walls are fully vertical and below a low-slope roof. The rain exposure category is medium, and the rain load predication is based on ASHRAE standard 160. According to a national regulation from the State Council *([2006] NO.28)*, the indoor temperature of buildings in China must above 26°C in summer and below 20°C in winter. So, current authors assume 26°C as the summer indoor temperature, the 20°C for winter, and the 23°C as the annual average value. Mentioned in the Code *Designing energy-efficient residential buildings in hot summer and cold winter zone*, the ventilation rate must be higher than 1.0 h^{-1} in AC period (summer). For the calculation period, it is set for five years, from the year 2018 to 2022. The same annual weather file from Meteonorm is used for these five years. All things mentioned above are inputs required by the WUFI® Pro but it becomes difficult to choose the orientation for simulation. Because orientation selection in WUFI® associates with other factors influencing mould risk:

·Solar incident radiation (on the outdoor surface);

·Wind Driven Rain;

·Convective heat transfer coefficient (a step-function of wind direction).

Therefore, it is not clear which orientation would be the most mould-vulnerable. Rather than randomly picking one, all eight orientations offered by *WUFI® Pro* are going to be simulated. According to yearly mould growth rate in all orientations which will be simulated later (Table 4), southeast is the most mould-vulnerable direction for all three cities. Therefore, the simulation process will be illustrated in this orientation.

2.4. Results and discussions

2.4.1. Hygrothermal condition and the water content in spores

The outcome of hygrothermal simulation (Figure 3) includes the temperature and humidity condition over five years. The X axis is the time in the unit of hour and the Y axis stands for the relative humidity and temperature respectively. From June to August each year (the rainy season), the relative humidity in three cities reaches the absolute maximum. It is higher than the critical threshold 80% which was recommended by IEA for preventing mould germination (H. Hens, 1992). Due to the mean humidity in three cities is around 70%, so the relative humidity can easily reach the 80%. The hygrothermal condition of Shanghai and Nanjing are similar, identified by two nearly overlapped charts. The humidity of Hangzhou is higher and fluctuates more drastically at the bottom of the chart. For the temperature, Shanghai and Nanjing still stay similar and with little variation, while Hangzhou still swingers bigger but lower than the other two.

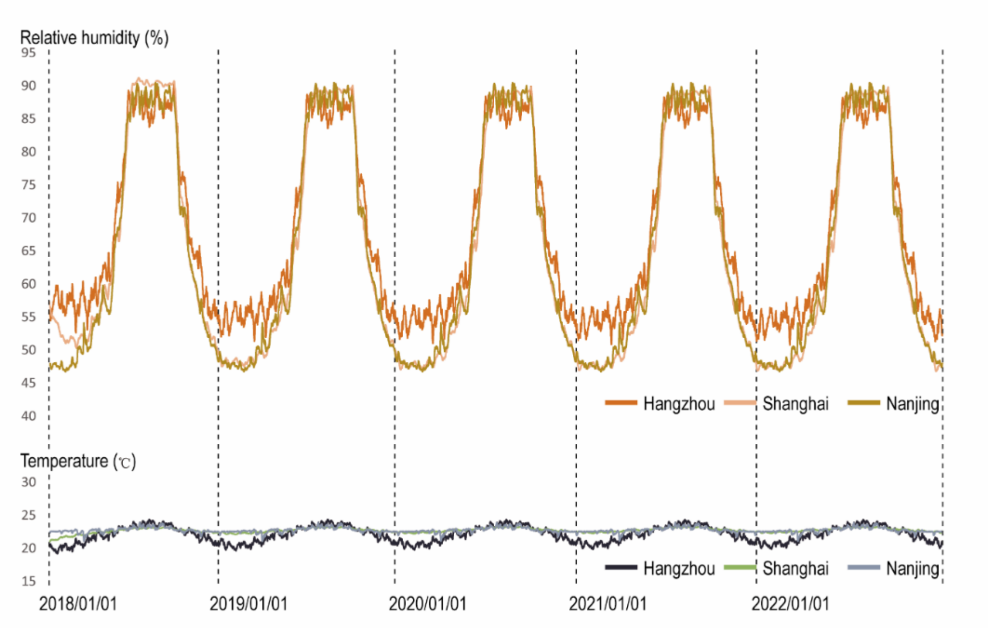


Figure 3: Hygrothermal situation on inner surface

Based on hygrothermal simulation results, WUFI® BIO calculates the water content in spores. For settings in the WUFI® BIO, the initial relative humidity is 50% while the substrate belongs to the class Ⅰ. Obtained outcomes (Figure 4) show that the Plum Rain Season is a crucial period for the water content each year. Starting from the June (the beginning of the rainy season), the water content of spores in all three walls rise speedily and overwhelmingly exceed the critical water content, which is only around 200 kg/m^3. They stay steady until the September and drop fast after that. Comparing the apex period of three cities, Shanghai is the highest and Nanjing is the second highest. Hangzhou has the least water content in spores but this number fluctuates more intensely.

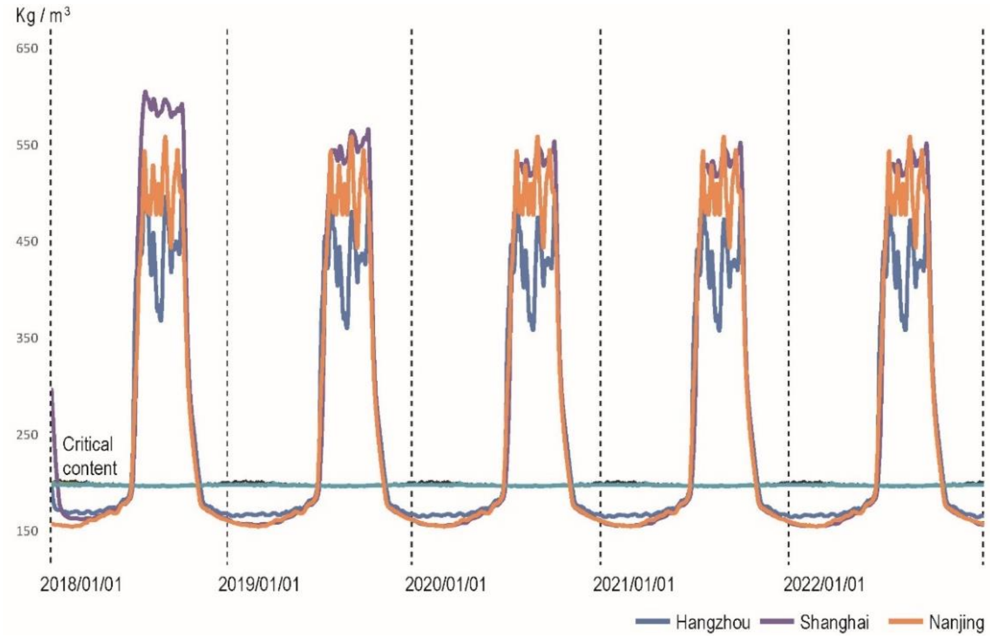


Figure 4: Water content in Spores

2.4.2. Mould growth rate and mould Index

After receiving results of water content in spores, the mould growth rate is simulated with the WUFI® BIO and WUFI® VTT. Table 4 demonstrates the mould growth rate of all eight orientations, and these statistics are visualized in a radar chart (Figure 5). South-east is the most mould-vulnerable orientation for all cities, and all radar diagrams match pictures of Wind-Driven-Rain orientation (included in Table 1).

Hangzhou has the highest time-average mould growth rate around 296 mm/year, the number of Shanghai is 438 mm/year, and Nanjing has the number about 273 mm/year. However, the lowest mould growth rate in three cities all exceed 200 mm/year, which means none of wall typologies is acceptable in the perspective of mould risk.

Table 4: Mould growth rate simulated by WUFI® BIO (mm/year)

	North	North west	West	South-west	South	South-east	East	North-east
Hang-zhou	287	291	291	292	295	296	293	289
Shanghai	435	436	437	437	438	438	437	436

Nanjing	269	271	271	271	272	273	272	270

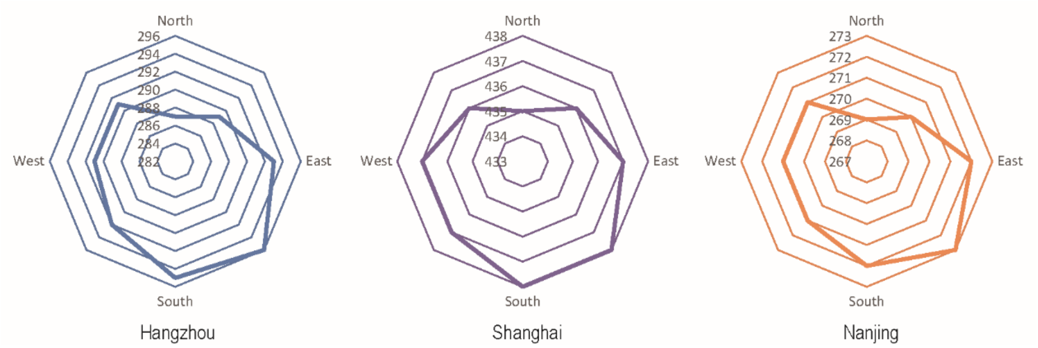


Figure 5: Mould growth rate in different orientations of all three cities

The mould index was initially coined by Viitanen and Ritschkoff to identify the mould problem more clearly (Viitanen & Ritschkoff, 1991). They divided the mould condition into six levels: level zero means no mould at all, the growth process starts from level one but only can be perceived with the microscope, the mould coverage in level two reaches 10% of the surface, mould growth in the level three is visible to the unaided eye, the coverages reach 10%, 50%, and 100% from level four to level six respectively.

In three testing cities, all the mould indexes have risen drastically since the first year June and arrive at a plain at the end of September (Figure 6). Shanghai has the highest mould index over the five years and stays still at 3.7. Hangzhou has a steep decrease at the beginning of the year 2019 but staying steady at the mould index 3. Nanjing is lower than Hangzhou during the first year but staying higher for the left four years. As what we introduced before, WUFI® BIO does not consider the unfavourable period but WUFI® VTT does. However, there is an observable decrease in Figure 6. Authors guess it is because of the competition in the mould group itself. The nutrition consumption speed does not support the mould staying at the same level.

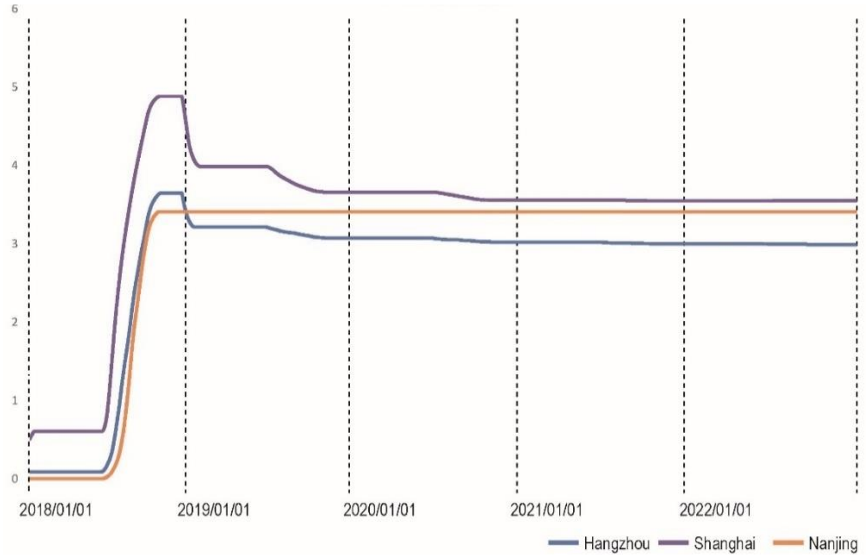


Figure 6: Mould index of three cities within the southeast orientation (By WUFI® BIO)

Based on a different calculation model, simulation results in WUFI® VTT (Figure 7) are more favourable than results in the WUFI® BIO. For settings in the WUFI® VTT, the building material is in the relatively low decline class with cleaned type of surface. The sensitivity class is set as medium resistant. Except the mould index of Shanghai still exceeds 2 which is unacceptable, both Nanjing and Hangzhou become less serious. The number of Nanjing is around 1.7 while Hangzhou has the lowest index at 1.5. All three cities have the turning point at the end of the September each year, since when the mould index starts decreasing before the rainy season in the next year.

Meanwhile, Shanghai has the highest mould index in both WUFI® VTT and WUFI® BIO. Nanjing is also higher than Hangzhou in two software. It is a validation of two calculation models behind the software. Simulation results confirm that the national wall composition atlas is not suitable for local building in Shanghai. That type of wall composition has a vast possibility bring the indoor mould. Though other two cities have their own locally official recommendations, the mould risk brought by the external wall is still lack of consideration and exploration.

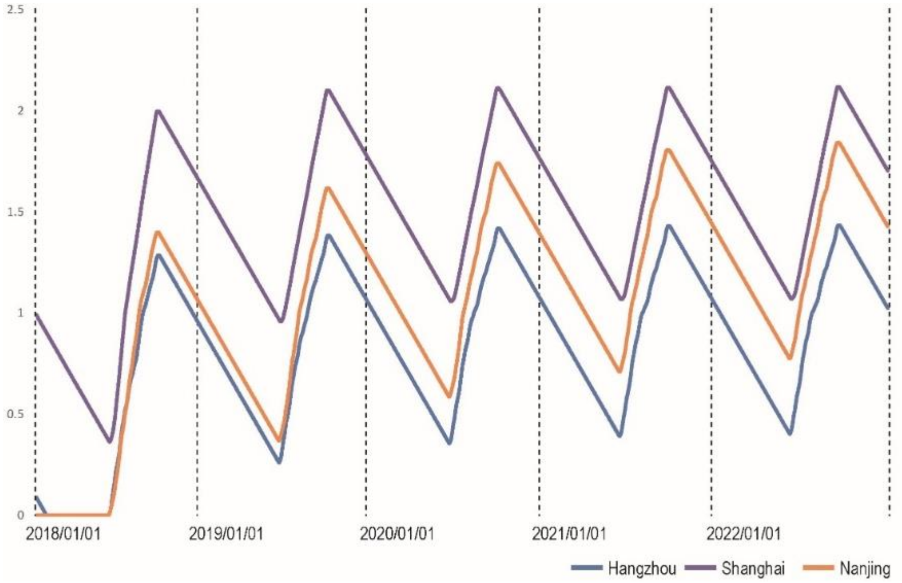


Figure 7: Mould index of three cities within the south-east orientation (By WUFI® VTT)

3. Reduce the mould risk during design

3.1. Overall consideration

An effective workflow is critical to gain the desirable indoor air quality (ASHREA, 2009). Although numerical models and software like WUFI exist to predict the mould risk, they only can verify the final design which has all decision variables decided, rather than helping the decision making during the design process. Meanwhile, it is impossible to quantify every design step because the majority of design decisions are made with qualitative considerations. Therefore, the chapter 3 tries to embed all strategies in different design steps and make a guiding matrix to guide architects.

To reduce the mould risk during the design stage, inducing variables should be correlated to design strategies first. Much less than nine variables proposed by Hens (2003), Sedlbauer (2001) deemed only four main ones are impacting on indoor mould: temperature, humidity, substrate, and exposure time in the critical hygro-thermal condition (easy for the spore germination). Since more essential design objectives (thermal comfort, internal heat gain, user habits) decide the internal surface temperature, normally it is illogical to change the surface temperature for the mould prevention, except special cases like rooms for surgery or preserving ancient books. Exposure time is another critical parameter for mould risk (Vereecken & Roels, 2012) because exposing to high humidity environment for a short period will not result in fungal growth if the previous period at low humidity is long enough (Viitanen et al., 2010, Møller, Andersen, Rode, & Peuhkuri, 2017). However, the exposure time is difficult to be corelated with design choices except that the inner surface of frequently-water-spilled rooms (showering rooms, toilets, and laundry rooms) should be waterproofed, in order to wipe the water easily for changing the exposure time. Therefore, authors assume that temperature and exposure time are not practically tuneable to avoid the mould in real design projects.

Not strongly driven by other more priority design objectives, only humidity and substrate characteristics (mainly refers to the mould-resistant ability) can be practically tuned for mould avoidance. As shown in Figure 8, the humidity consideration is related to more design chances. In accordance with different duties, design strategies associated with the humidity can be categorized into: lead the water away from the project site, keep the rest of water out of the building, limit the mould growth while moisture dries out (make it less prone to moisture retention or mould growth) (Harriman & Neil, 2006). For the material (substrate) selection, it is majorly based on the envelope design. Detailed relationships will be discussed in the following subsections.

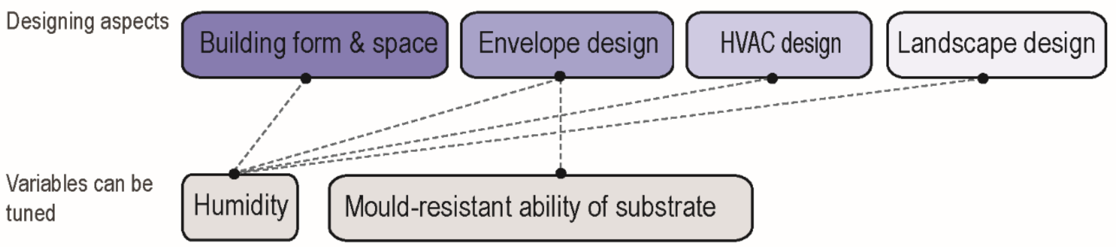


Figure 8: Relationship between designing aspects and variables for mould reduction

3.2. Building form and space design

WUFI® Pro requires two factors of building geometry as inputs: building height and wall inclination. They do influence the mould formation, for example, higher building receives more Wind-Driven-Rain (Karaglozls & Hadjlsophocleous, n.d.). However, both the building height and the wall inclination cannot be considered for the mould-free design. Because for real construction projects, they are decided by more important objectives like making more spaces for the financial profit, rather than the mould avoidance. This issue also identifies the importance of the current study which aims to connect the building science and building design. Traditional investigations were only studied in the scope of mould risk but neglecting the reality of a design project, which is driven by many other objectives.

Comparing with these two factors, the roof design, which conveys precipitation to the drainage system, is more viable for the mould prevention. When we design the roof shape, the total rainfall volume should be carefully calculated before considering the rain diversion routine and also the roof inclination. On top of that, the distance of roof overhangs also should be deliberately computed, because sometimes they can cut more than 50% of the water streaming down to a wall (Harriman & Neil, 2006).

In addition to the roof, the mould risk is also influenced by the building entrance which connects the internal space and the external weather. Therefore, a transitional zone like closed porch or vestibule is necessary for some extremely damp areas, because of the drastically internal humidity change once the door is opened. To take away the extra moisture during the interior space design, the uniformity of the layout from floor to floor, space usage, which affects air distribution and ventilation should be taken into account. Meanwhile, the irregular or trivial form should be avoided in case of the water retention on them. On the other side, according to the contact angle between a water drop and the surface, details like the roof drip-edge can be deliberately designed to facilitate the water dropping down (Rose, 2005). Not only the detail design itself, but mistakes coming from workmanship are also crucial to be considered. Therefore, the design also should be easily understood and constructed.

3.3. Envelope design

3.3.1. Decrease the humidity with envelope design

When the facade is facing the water-landscape, architects like large windows or balconies opened into the water-landscape for desirable views. However, this kind of fenestration also brings a higher airborne moisture load which may lead to the indoor mould. Therefore, the operable area of a window should be carefully considered. Directly blocking the external moisture can be achieved not only by less opening area, the vapor retarder also plays a vital role in it (Trechsel & Bomberg, 2010). The majority of buildings across the Yangtze River Delta have vapour retarders only for the roof and the basement, other than on facades. Thence the water retarder can be added to reduce the mould risk in critical occasions. Nevertheless, water retarders containing hydrocarbons are easy to be evaporated over hot weather that can lead to cracking and leakage, which will be main channels of the moisture transportation (Rose, 2005).

On top of the vapour retarder, the insulation layer is another cause of extra-moisture (Orlik-Kozdoń & Steidl, 2017). Due to different hygroscopic characteristics, some insulation materials absorb more moisture than others, and that results in different relative humidity. After being humidified one hour per day and for ten days, the relative humidity increased 5% in houses insulated by cellulose and boosted 30% in the house insulated with mineral wool (Mlakar & Štrancar, 2013). Insulation layer also strongly relates to the condensation which brings the water formation. The condensation resistance factor f_{Rsi} was proposed by International Energy Agency (IEA) to check the condensation risk (H Hens, 1990). The value of f_{Rsi} is mainly decided by the thermal resistance of the total envelope and the internal finishing layer. Many countries other than China have their own requirements on f_{Rsi} to avoid the condensation: $f_{0.2}$ ≥0.7 in Belgium, f_{Rsi}≥0.65 in Netherland, and f_{Rsi}≥0.7 in German. If the condensation appears on thermal bridges, insulating rendering coat can be applied to reduce the mould risk (Fantucci, Isaia, Serra, & Dutto, 2017).

Condensation not only happens on the insulation layer, but also occurs on the facade finishing layer. Due to its heat capacity has a substantial impact on the envelope temperature fluctuation, the finishing layer on facades is closely associated with the condensation (Elisa, 2013) which leads to mould. Especially on the surface of northern wall, heat capacity is most influential of mould growth because of condensation (S. Johansson, Wadsö, & Sandin, 2010). Scholars (S. Johansson, Wadsö, & Sandin, 2005) found that the nocturnal temperature on finishing layer with high thermal capacity was 0.5K higher than on the surface with low heat capacity. That means lower condensation risk and mould risk for the material with high heat capacity. Besides the heat capacity, the hydrophilic property also should be considered for selecting the finishing layer.

Increasingly raised envelope-airtightness aimed to improve building energy efficiency is another cause of the extra indoor moisture. The raised airtightness creates new ways of heat and moisture transportation, which block the internal moisture passing through the envelope (Elisa, 2013). Nevertheless, in winter the Yangtze River Delta does not offer central heating, so the airtightness only contributes during the cooling period (AC period). Moreover, many buildings need higher air leakage rate due to no mechanical ventilation, thence the airtightness of building envelope in the Yangtze River Delta may not need to be as high as in other areas.

3.3.2. Increase materials' ability of mould resistant

Selecting mould-resistant materials is the other approach to reduce mould risk during the envelope design. Many construction products are organically made to be environmentally friendly but that also makes them good substrates for the mould growth. For instance, common glue and wallpaper are desirable substrates for the majority of indoor fungal (Haleem Khan & Mohan Karuppayil, 2012, Hyvärinen, Meklin, Vepsäläinen, & Nevalainen, 2002). The threshold of humidity and exposure time for spore germination is higher in materials stone-based than wood-based (Ritschkoff, Viitanen, & Koskela, 2000). Therefore, construction products made from mineral and ceramics which contain less organic matter should be selected with priority (P. Johansson, 2014). Actually mould even can appear on the mould-resistant material which is contaminated by organic dust (Chang, Foarde, & VanOsdell, 1996). To avoid this problem, nonporous and low-texture materials that cannot harbour dust or nutrients are preferred (Warsco & Lindsey, 2003).

In accordance with their mould-resistant abilities, Sedlbauer (2001b) categorized substrates into four classes. Most of construction materials belong to the category two which are biologically adverse recyclable. China also has issued related standards on the mould issue of three construction products. Based on their mould resistance, there are 2 different levels for building sealants, 5 levels for wooden decoration boards, and also 5 levels for building painting productions. When architects do the decision makings on material designation, these indexes should be considered.

3.4. Ventilation, air conditioning, and pressurization (VACP)

The VACP design is not architects' direct duty but it should be known for their role as a design team leader. The indoor dampness and mould risk are strongly related to ventilation (H. Moon & Augenbroe, 2004, H. L. S. C. Hens, 1999), which can remove or dilute the air moisture, and also exhuast airboren spores or contaminants (Warsco & Lindsey, 2003). Due to no central HVAC system in most buildings across the Yangtze River Delta, only stack and wind induced ventilation can be applied to. However, during the Plum Rain Season, windows are usually closed thence even the natural ventilation is difficult to obtain. After three years measuring, eight out of ten homes in Shanghai only with natural ventilation were found to have a ventilation rate lower than 0.5 h^{-1} (Wang, 2011). There is no successful case which solely utilizes passive ventilating strategies. For buildings in the Yangtze River Delta, only mechanical or half-mechanical ventilation system can be really helpful (Wang, 2011).

During the summer period in Yangtze River Delta, the majority of homes use domestic air-conditioners for cooling which also can extract the moisture out of the room. When the air is cooled and the relative humidity (RH) becomes 100%, the moisture will condense on the cooling coils because the air is unable to hold more water vapour. At the same time, many domestic air-conditioners have mould inside but it receives even less attention comparing with indoor mould on the wall. Appropriate sizing of air conditioners becomes necessary to reduce the mould risk (Warsco & Lindsey, 2003).

Pressurization is another way to keep moisture out by the positive pressure between indoor and outside (Chen, Claridge, Rohrs, & Liao, 2016). Nevertheless, this method is only useful for a limited space rather than a whole building because static pressures in the same building differ from one space to another, due to the stack effect and the HVAC operation (ASHRAE, 2009). Meanwhile, except the fire escape staircase in high-rise buildings which utilise the pressurization to keep out smoke for evacuation, other common buildings do not have any pressurization facilities. It is not applicable to popularize this approach.

3.5. Landscape design

Landscape design also plays a role lowering the mould risk. No need for daily watering nor releasing much water molecules, Xeriscape (drought-tolerant plants) can help buildings escape the excessive moisture load (Harriman & Neil, 2006). On the other hand, the fountain or pool can be avoided in extremely moist areas. Meanwhile, the mould-spore concentration rate in the greened room is lower than a not greened one (Fantucci et al., 2017). With the help of new tech, a living wall system can be utilised not only outside but also indoor.

3.6. Matrix for the decision making

This sub-chapter tries to embed all strategies in different design steps and make a guiding matrix (Figure 9) for architects. According to the Chinese code *Standard of design depth in construction documentation*, the design phase of common projects can be divided into: Concept & schematic Design, Development Design and Construction-document Design. The matrix chronologically follows this sequence while categorizing strategies from previous chapters. Although this Matrix follows the Chinese code, it still can be applied to projects in other countries with little change. Because these stage divisions are more or less the same in different countries. For example, by the American Institute of Architects (AIA), one design project is similarly divided into Programming, Schematic Design, Design Development, Preparation of Construction Documents.

	Building form & space	Envelope	VACP	Landscape
Conceptual design	• Exposurethe building to sunlight • Orientate the building to prevailing winds • Avoid trivial building form	• Avoid trivial facade skin	N/A	• Keep the building a distance from wetlands
Schematic design	• Calculate the roof inclination • Avoid trivial building details • Set transitional zones • Alignment exterior wall openings with interior partioner and openings to facilitate cross-ventilation	• Control the ratio betwwen window to wall • Junctions between wall and openings should be easy for water flowing • Roughly material selection	N/A	• Use xeriscape • Avoid fountain or pool if the climate is humid
Development design	• Confirm the roof inclination • Avoid building details in trivial form	• Add vapor retarder • Manually check condensation • Trade-off between air-tightness and over-load moisture • Material selection (low mould-susceptability, high heat capacity of finishing layer) • Simulate the mould index with software	• Ventilation design • Size the Air-conditioner appropriately	• Select the xeriscape in detail • Drainage system design in the site plan
Construction drawing design	• Reconfirm the roof inlination	• Confirm the thickness of Insulation layer • Confirm the material selection • Condensation re-check • Resimulate the mould index with software	• Confirm the system sizing	• The material selection and composition design of flower bed which are close to the building

Figure 9: Matrix reducing mould risk during the whole design process

4. Conclusions

Although the indoor mould problem broadly exists over the Yangtze River Delta, rare attention has been paid to prevent it. There is a vast need for associated research and policies to address this issue. With computational simulation, authors of this paper quantified the indoor mould risk across that region (Hangzhou, Shanghai and Nanjing). Simulation results confirmed that all three cases have a high mould risk, especially Shanghai. The southeast is the most vulnerable direction for three cities: Hangzhou has a max mould growth rate of 296 mm/year, Nanjing has the rate around 273 mm/year, and Shanghai reaches 438 mm/year. In fact, the real situation is even worse because this simulation was conducted in the steady state condition.

After obtaining the mould risk scenario, authors analysed variables related to the mould risk and found that only the humidity and the substrate properties can be practically tuned to prevent the mould. Subsequently, this paper scrutinized and categorized all the design strategies. In the end, a design strategy matrix identifying all chances during the whole design stage was presented. The matrix showed that the Development Design Stage is the most important period for the mould prevention while the envelope design has more opportunities to reduce the mould risk.

The current study also has many limitations. First, there is no on-site data to validate the simulation. Second, the simulation only deals with the wall rather than a whole building. Third, due to the second point, authors are unable to use simulation to confirm the usefulness of design strategies from the chapter 3. However, due to there is limited studies considering the mould risk during the design stage, this paper is still beneficial in raising awareness of the relationship between building design and the mould risk.

Acknowledgements

This work is supported by under the Grant [ ]. Many thanks to two anonymous reviewers who proposed detailed suggestions.

References

ASHRAE. (2012). *ASHRAE Position Document on Limiting Indoor Mold and Dampness in Buildings*.

ASHREA. (2009). *Indoor Air Quality Guide*.

Baike. (2016). 梅雨季节[Plum season]. Retrieved from http://baike.baidu.com/item/梅雨季节/32325

Chang, J. C. S., Foarde, K. K., & VanOsdell, D. W. (1996). Assessment of fungal (Penicillium chrysogenum) growth on three HVAC duct materials. *Environment International*, *22*(4), 425–431. https://doi.org/10.1016/0160-4120(96)00030-X

Chen, W. J., Claridge, D. E., Rohrs, C., & Liao, J. (2016). Modeling to predict positive pressurization required to control mold growth from infiltration in buildings in a hot and humid climate. *Building and Environment*, *104*, 102–113. https://doi.org/10.1016/j.buildenv.2016.05.001

Elisa, G. (2013). *Nearly Zero Energy Buildings and Proliferation of Microorganisms*.

Springer.

Fantucci, S., Isaia, F., Serra, V., & Dutto, M. (2017). Insulating coat to prevent mold growth in thermal bridges. *Energy Procedia*, *134*, 414–422. https://doi.org/10.1016/j.egypro.2017.09.591

FRAUNHOFER BUILDING INNOVATION. (2017). WUFI® Bio. Retrieved from https://wufi.de/en/2017/03/31/wufi-bio/

Häglund, M., Isaksson, T., & Thelandersson, S. (2010). Onset of mould growth - the effect of climate variability and different geographic locations. In *Irg/Wp 10-20446* (p. 10).

Haleem Khan, A. A., & Mohan Karuppayil, S. (2012). Fungal pollution of indoor environments and its management. *Saudi Journal of Biological Sciences*, *19*(4), 405–426. https://doi.org/10.1016/j.sjbs.2012.06.002

Harriman, L., & Neil, L. (2006). *Reducing Mold Risk*. California.

Hens, H. (1990). ANNEX 14: CONDENSATION AND ENERGY. In *Guidelines & Practice INTERNATIONAL ENERGY AGENCY -ENERGY CONSERVATION IN BUILDING AND COMMUNITY SYSTEMS PROGRAMME* (Vol. 2). Retrieved from http://www.ecbcs.org/docs/annex_14_guidelines_and_practice.pdf

Hens, H. (1992). IEA Annex 14: Condensation and Energy. *Journal of Thermal Insulation*, *15*(3), 261–273. https://doi.org/10.1177/109719639201500307

Hens, H. (2003). Mold in dwellings: field studies in a moderate climate. *Proceedings of the 24th AIVC Conference and BETEC Conference, Ventilation, Humidity Control and Energy*, 12–14. Retrieved from http://www.kuleuven.be/bwf/projects/annex41/protected/data/KUL Apr 2006 Paper A41-T4-B-06-5.pdf

Hens, H. L. S. C. (1999). Fungal defacement in buildings: A performance related approach. *HVAC and R Research*, *5*(3), 265–280. https://doi.org/10.1080/10789669.1999.10391237

Hyvärinen, A., Meklin, T., Vepsäläinen, A., & Nevalainen, A. (2002). Fungi and actinobacteria in moisture-damaged building materials - Concentrations and diversity. *International Biodeterioration and Biodegradation*, *49*(1), 27–37. https://doi.org/10.1016/S0964-8305(01)00103-2

Johansson, P. (2014). *Determination of the Critical Moisture Level for Mould Growth on Building Materials*. Lund University.

Johansson, S., Wadsö, L., & Sandin, K. (2005). Microbial growth on buildings facades with thin rendering on thermal insulation. *7 Th Nordic Building Physics Symposium* *in Reykjavik*. Retrieved from http://web.byv.kth.se/bphys/reykjavik/pdf/art_169.pdf

Johansson, S., Wadsö, L., & Sandin, K. (2010). Estimation of mould growth levels on rendered fa??ades based on surface relative humidity and surface temperature measurements. *Building and Environment*, *45*(5), 1153–1160. https://doi.org/10.1016/j.buildenv.2009.10.022

Karaglozls, A., & Hadjlsophocleous, G. (n.d.). *WIND-DRIVEN RAIN ON HIGH-RISE BUILDINGS*. Retrieved from https://web.ornl.gov/sci/buildings/conf-archive/1995 B6 papers/044_Karagiozis.pdf

Mlakar, J., & Štrancar, J. (2013). Temperature and humidity profiles in passive-house building blocks. *Building and Environment*, *60*, 185–193. https://doi.org/10.1016/j.buildenv.2012.11.018

Møller, E. B., Andersen, B., Rode, C., & Peuhkuri, R. (2017). Conditions for mould growth on typical interior surfaces. *Energy Procedia*, *132*, 171–176. https://doi.org/10.1016/j.egypro.2017.09.680

Moon, H., & Augenbroe, G. (2004). FUTURE RESEARCH NEEDS FOR MOLD GROWTH RISK ANALYSIS. In *Proceedings of the CIB World Building Congress* (pp. 1–10). Retrieved from http://www.irbnet.de/daten/iconda/CIB1772.pdf

Moon, H. J., & Augenbroe, G. (2003). Evaluation of Hygrothermal Models for Mold Growth Avoidance Prediction. *Eighth International IBPSA Conference Eindhoven, Netherlands August 11-14, 2003*, 895–902.

Nunez, M., & Hammer, H. (2014). Microbial specialists in below-grade foundation walls in Scandinavia. *Indoor Air*, *24*(5), 543–551. https://doi.org/10.1111/ina.12095

Orlik-Kozdoń, B., & Steidl, T. (2017). Impact of internal insulation on the hygrothermal performance of brick wall. *Journal of Building Physics*, *41*(2), 120–134. https://doi.org/10.1177/1744259116671322

Ritschkoff, A., Viitanen, H., & Koskela, K. (2000). The response of building materials to the mould exposure at different response conditions. In *Proceedings of Healthy Buildings 2000* (p. 317). Espoo.

Rose, W. B. (2005). *Water in buildings: an architect's guide to moisture and mold*. Hoboken, New Jersey, United States: Wiley.

Sedlbauer, K. (2001a). *Prediction of mould fungus formation on the surface of/and inside building components*. Fraunhofer Institute. Retrieved from http://www.ibp.fraunhofer.de/content/dam/ibp/en/documents/ks_dissertation_etcm1021-30729.pdf

Sedlbauer, K. (2001b). *Vorhersage von Schimmelpilzbildung auf und in Bauteilen [Prediction of mold formation on and in components]*. Universität Stuttgart.

Trechsel, H., & Bomberg, M. T. (2010). *Moisture Control in Buildings: The Key Factor in Mold Prevention*. *ASTM International* (2nd ed.). West Conshohocken, Philadelphia: ASTM International. Retrieved from http://books.google.com/books?hl=en&lr=&id=_pc6X3yvYsIC&oi=fnd&pg=PP12&dq=Moisture+Control+in+Buildings&ots=QgO5w40Wk7&sig=8cSZNTT853t2rWIGjxS0TpcCbdA

U.S. Environmental Protection Agency. (2012). *A Brief Guide to Mold, Moisture,And Your Home*.

U.S. Environmental Protection Agency. (2013). *Moisture Control Guidance for Building Design , Construction and Maintenance*.

Vereecken, E., & Roels, S. (2012). Review of mould prediction models and their influence on mould risk evaluation. *Building and Environment*, *51*(April 2017), 296–310. https://doi.org/10.1016/j.buildenv.2011.11.003

Viitanen, H., & Ritschkoff, A. (1991). *Mould growth in pine and spruce sapwood in relation to air humidity and temperature*. Uppsala: Swedish University of Agricultural Sciences.

Viitanen, H., Vinha, J., Salminen, K., Ojanen, T., Peuhkuri, R., Paajanen, L., & Lahdesmaki, K. (2010). Moisture and Bio-deterioration Risk of Building Materials and Structures. *Journal of Building Physics*, *33*(3), 201–224. https://doi.org/10.1177/1744259109343511

Wang, Z. (2011). 机械通风是解决中国住宅室内通风问题的最佳方法 [Mechanical ventilation is the best way to solve the ventilation problem in chinese residential buildings]. Retrieved from https://wenku.baidu.com/view/dfaebfc76137ee06eff918a7.html

Warsco, K., & Lindsey, P. F. (2003). Proactive approaches for mold-free interior environments. *Archives of Environmental Health*, *58*(8), 512–22. https://doi.org/10.3200/AEOH.58.8.512-522

Wei, X. (2016). 上海市居住建筑室内墙体表面霉菌生长调研[Study on Mould Growth in Dwelling Building of Shanghai]. *建筑热能通风空调[Building Energy & Environment]*, *35*(1), 27–30.