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Møller, Eva B.; Aagaard, Niels-Jørgen

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Moisture risks arising from retrofitting – The safest technical solution is not always the best solution

Eva B. Møller[1], Niels-Jørgen Aagaard[2]

Abstract

In the coming years insulation in buildings will need to be retrofitted to save energy. The article focuses on the difficulty in choosing the best way of retrofitting the insulation as e.g. safety, aesthetics and costs are often prioritised differently in each project, depending on the context for the building and the building owner. As an example, the paper describes risks arising from retrofitting with emphasis on moisture safety, as high moisture levels may lead to health problems for the building users. The example illustrates the difficulty in obtaining moisture safety and energy savings at the same time when retrofitting by internal insulation.

However, moisture-related health risks are mainly personal, as they depend i.a. on age, gender and medical history. This raises the question of whether the building owner should be allowed to choose whatever he wants, with the risk of extreme prioritisations, or whether society should ban some solutions, because they may be too risky for some building users. On the other hand, can society afford to make all retrofitting safe also for the weakest? Based on a review of literature, the paper outlines how these dilemmas are described and handled in Denmark today. The aim is to operate with a combination of information on why some solutions pose more risks than others and descriptions on how the risks are reduced. The best solution is found by weighting potential energy savings, costs, aesthetics and health risks. Consequently, the best solution is not necessarily the safest technical solution; it depends on an evaluation by the building owner or user.

However, the risk is not quantified. To make the decision more objective in the future, a more quantified prioritisation might be possible by defining moisture safety classes for buildings, describing which buildings should only be used by people who are not prone to moisture-related health problems and which can be used by more sensitive users.

Keywords: Retrofitting of insulation, prioritising, moisture safety level, health, costs

1. Introduction

In Denmark, the expected life time of buildings is 70-100 years (de Place Hansen, 2010). Consequently, most buildings are retrofitted at least once during their life time. There are

[1] Senior researcher; Department of Construction and health, Danish Building Research Institute / Aalborg University, A.C Meyers Vænge 15, DK- 2450 Copenhagen SV, Denmark. evm@ sbi.aau.dk
[2] Research director; Department of Construction and health, Danish Building Research Institute / Aalborg University, A.C Meyers Vænge 15, DK- 2450 Copenhagen SV, Denmark. nja@sbi.aau.dk

many reasons for retrofitting and they are often a combination of factors: a need of repairs, a desire for improved comfort and indoor climate, handling of social problems or improvement of energy performance (Møller et al., 2011). Retrofitting can be executed in many ways and typically differs on costs, aesthetics, structural design, robustness and moisture risk. One solution is rarely optimal on every parameter and therefore a building owner must prioritise. A solution can be unacceptable in one case, but be the best solution in another case. Consultants often suggest the safest solution. However, that solution may be expensive or change the appearance of the building and the solution would therefore be unacceptable to some building owners, while other building owners would prioritise safety more. Furthermore, authorities may have limits as regards what is acceptable from an aesthetic, economical and health point of view.

The paper outlines these issues with examples of moisture risk arising from interior insulation. In principle, most of the issues also apply to other risks and methods of retrofitting.

2. Designing moisture safe buildings today – acceptable solutions

Most countries have standards for structural design based on probabilistic modelling of loads and capacities (CEN, 2000), which include the level of acceptable risk. Moisture design, on the other hand, is in its infancy. WHO (2010) concluded: “Building standards and regulations with regard to comfort and health do not sufficiently emphasize requirements for preventing and controlling excess moisture and dampness.” There are standards describing humidity loads e.g. EN ISO 13788 (European Standard, 2001), but this standard is not referred to in the Danish Building Regulations and moisture safety is only described in very broad terms, e.g. that retrofitting must be moisture safe. However, it is not defined what is meant by moisture safe retrofitting. Consequently, an acceptable level of moisture is not defined.

Therefore, risk assessment today is based on professionals assessing different materials properties and measurements e.g. humidity levels and ventilation rates in existing buildings. By combining this with guidelines, experience, calculations and knowledge of the future use of the building, the professionals propose what solutions they believe to be acceptable.

Pietrzyk & Hagentoft (2008) proposed a method for estimating the probability of a design providing proper conditions in the building under various conditions. This was followed up by new initiatives such as IEA-ECBCS Annex 55 (2012) to develop and validate probabilistic tools for hygrothermal performance of energy retrofitting measures. The aim is to use probabilistic methods to provide reliable ranges for the outcome (e.g. humidity) making moisture risk assessment quantifiable.

3. Moisture risks arising from retrofitting

Some retrofits solve one problem but create another one, and some retrofits are ineffective or inadequate (Møller et al., 2011). Some retrofits are safer than others, e.g. repairs that only restore the performance of the building without adding new value can be relatively safe. If no changes of a building physical nature are made, the building performs like it did before the repair was necessary. Major repairs are often only one part of retrofitting; when major repairs are necessary, the building has probably reached an age when its original performance no longer complies with modern standards. Especially energy performance, comfort and layout are areas where an existing building often needs modernisation.

3.1 Retrofitting through additional insulation – the theoretical understanding

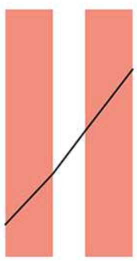
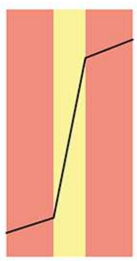
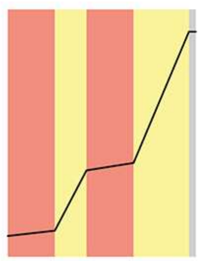
Buildings account for approximately 40 % of the energy consumption in the EU (European Parliament, 2010). It is therefore to be expected that retrofitting will in the future include measures to reduce the energy consumption in existing buildings. However, practice shows that sometimes moisture problems arise from retrofitting. These problems might be further aggravated as requirements to energy performance are tightened.

When buildings are retrofitted to reduce energy consumption, it is necessary to increase focus on moisture transport as heat and moisture transport is connected:

- Heat can dry out moisture; consequently, the potential for drying out is reduced if the heat flow is decreased.
- Hot air can hold more water vapour than cold air; consequently, decreasing the temperature will raise the relative humidity

The location of the insulation material is decisive for the temperature distribution and therefore for the moisture behaviour of the wall. Table 1 shows a cavity wall with different kinds of additional insulation. In the insulated examples, the cavity is filled with mineral wool (λ-value: 0.044 W/m·K). The interior insulation consists of mineral wool and battens (combined λ-value: 0.045 W/m·K), vapour retarder and a 2 x 13 mm gypsum board. The exterior insulation material is mineral wool (λ-value: 0.038 W/m·K) with exterior rendering. The calculation is made by a simple Glaser calculation according to EN ISO 13788 (European Standard, 2001), based on outdoor climate according to the Danish Design Reference Year (DRY).

Table 1: Temperature distribution through a cavity brick wall depending on where the added insulation is placed. Outside is on the left.

	No insulation	Cavity insulation	Cavity insulation + interior insulation	Cavity insulation + exterior insulation
Section of brick wall: Cavity: 70 mm Interior and exterior insulation: 150 mm Outdoor temp.: -1.1 °C Indoor temp.: 20 °C				
Outdoor surface	- 0.5 °C	- 0.8 °C	- 1.0 °C	- 1.0 °C
Inside inner leaf	18.1 °C	19.1 °C	8.1 °C	19.6 °C
Indoor surface	18.1 °C	19.1 °C	19.6 °C	19.6 °C

If the vapour retarder is intact in the example of the added interior insulation, there is no problem with diffusion through the insulation material. However, if the vapour retarder is defective, humid indoor air will pass through the mineral wool and reach the former inside of the wall (inside inner leaf), then condensation will occur with a risk of degradation of the battens.

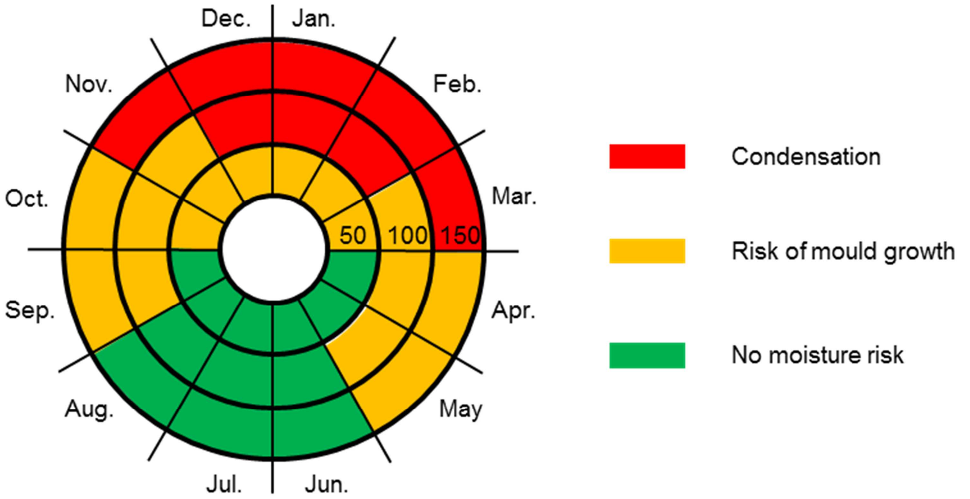


Figure 1: Moisture risk behind interior insulation with different thicknesses, over a whole year. Inner circle: 50 mm, middle circle: 100 mm, outer circle: 150 mm

Avoiding condensation is not enough; condensation might result in degradation of organic materials, but mould growth can occur at lower humidity levels; 75 % RH at 25 °C is considered the lowest humidity level on easy accessible materials like paper and cardboard (Sedlbauer, 2001). At lower temperatures, the limit is higher. In Figure 1, the example of interior insulation in Table 1 has been repeated for every month, showing how condensation and risk of mould growth increase with increased insulation; tightness of the vapour barrier becomes more critical with improved insulation.

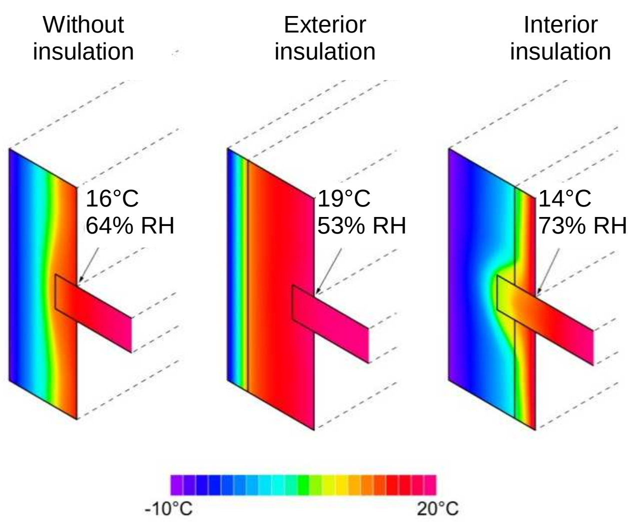


Figure 2: Temperature and relative humidity at thermal bridges depending on where insulation material is installed (Møller, 2012).

Even if the vapour barrier is tight and other prerequisites are met, interior insulation can still be risky from a moisture point of view. Figure 2 illustrates the effect of a thermal bridge in a solid brick wall with a suspended concrete floor, where 100 mm mineral wool is added both at the exterior and the interior side, the outdoor temperature is – 1.1°C and the indoor temperature is + 20 °C.

The lower temperature at the thermal bridges results in high relative humidity. In buildings with a wooden joist system, the thermal bridge at the beam ends will be less extreme. However, wooden floors are not airtight, so humid indoor air will reach the cold area at the beam ends, resulting in condensation or mould growth. In order to prevent this, the temperature in the area must be raised. Morelli et al., (2010) showed that this can be achieved by finishing a 200 mm interior insulation material at approximately 300 mm above and below the floor division. This will reduce the moisture risk but also the energy savings.

3.2 Retrofitting to save energy – controlling the airflow

Ventilation is responsible for 20-30 % of the total heat loss in existing dwellings in Denmark (Wittchen, 2004). Reducing the airflow is therefore also a way of reducing the heat loss. Many older buildings have a high natural air change rate as a result of air leakages in the building envelope. Tightening the building will reduce this. As a consequence, the airflow will be more controlled, the air change rate will no longer depend on the weather and the humid air will no longer find its way through random cracks in the building envelope in places where condensation may occur. The air change rate will be reduced and thereby the heat loss. However, it is necessary to have a minimum air change rate as the relative humidity in the indoor air will otherwise become too high because of the moisture produced by human activities. It is therefore necessary actively to provide sufficient ventilation. It is normally sufficient to open windows to make a thorough airing a few times a day for 10-15 minutes. However, experience shows that for some users this is difficult to accommodate.

Some users do not ventilate as much as recommended, while other users do ventilate, but have a high moisture production and should therefore ventilate more than usual. Figure 1 would change with user behaviour that is different from what is considered normal. Ventilation rates can be mechanically controlled so that users no longer have to open the windows themselves. Unfortunately, many mechanical ventilation systems have to be adjusted and maintained, which practice has shown to be difficult for the ordinary user to do. As a result many ventilation systems in single-family homes do not function optimally (Knudsen et al., 2012).

4. Considerations of the building owner

When a building owner decides to retrofit a building, his reasons for choosing a specific solution is influenced by the way he uses the building. Whether he himself uses it, or whether he rents it out, will to some degree influence his view on costs, aesthetics, comfort and health risks. The best solution is found by weighting the different parameters and the best solution might change over time as energy prices, construction costs, demands for comfort, climate and fashion change.

4.1 Cost efficiency

If the building envelope is to be retrofitted, the Danish Building Regulations (Danish Enterprise and Construction Authority, 2010) stipulate that cost-effective thermal insulation must be applied if it is moisture safe. Moisture safety is not defined, but energy-saving measures are cost efficient if:

$$\frac{(\text{Annual savings}) \cdot (\text{lifetime of measure})}{\text{Investment}} > 1.33$$

This is considered unproblematic by society and the building owner who uses his own building; as savings and costs end up in the same place. However, if the building is rented out, the user benefits from the annual savings while the owner must pay the investment.

4.2 Aesthetics

The appearance of a building is not always just a question of the cultural and personal preferences of the building owner. Especially in older urban districts, some buildings are listed, considered worth preserving or are otherwise subject to strict district plans. In such cases, the architectural freedom will be limited and interior insulation is often the only way to reduce the heat loss through the facades of buildings. In areas where buildings or the building stock have little or no architectural value or there are very few restrictions by the municipalities, it is up to the building owner to decide if and how the appearance of a building is to be changed. Some owners want to preserve the architectural expression, and interior insulation is therefore the only option for reducing the heat loss. Other building owners may have a wish to change the appearance of the building, and in such cases exterior insulation is a good solution.

4.3 Technical and economic barriers

The actual building morphology has a strong impact on the level of energy savings and the cost of retrofitting and consequently what type of additional insulation to choose. In some cases, balconies, exterior staircases or the like make it very complicated to retrofit the building envelope by exterior insulation, either because severe thermal bridges from the outside are introduced or it becomes very expensive to remove and re-construct such ‘extremities’. In some cases, technical installations in or close to the outer wall would have to be moved, which can be expensive. The floor area will be reduced and in some rooms this can limit the options for decorating. In such cases, indoor insulation might be preferable. Under other circumstances exterior insulation might be preferable, e.g. on numerous inner walls or suspended floors, which means thermal bridges from the inside resulting in decreased potential energy savings.

4.4 Ownership

In theory, the building owner’s considerations may be the same whether he uses the building himself or rents out, but in practice his views on the different parameters may be different in the two situations.

4.4.1 Building owner = building user

If the building owner uses the building himself, then he knows directly what is important for the building user. At some point, he will probably sell his building and must therefore take into consideration, how much the value of his building will change as a result of the retrofitting. Improved comfort is difficult to price. However, as a building user and an owner he knows how important it is to him personally that furniture does not have to be placed 10 cm from the outer walls, that the building is not draughty and that children can play on the floor without feeling cold.

Building dampness is strongly suspected of causing health problems e.g. respiratory symptoms and infections, and atopic and allergic people are especially susceptible (WHO, 2010). Health risks are therefore personal and depends i.a. on age, gender and medical history. All these factors will be known to the building owner, who can decide, whether he is willing to take a health risk, because his health is at low risk of being affected by a damp building, his ventilation habits are sound, moisture production is low and he can gain other benefits.

4.4.2 Building owner rents out the building

If the building owner rents out the building, he often focuses on economy as the value of the building depends on how much the tenants are willing to pay. Location is an important factor, but it cannot be changed by retrofitting. However, retrofitting can change how popular a location is; this is why retrofitting is used to change areas with social problems into more attractive areas (Danish Ministry of Refugee, Immigration and Integration Affairs, 2004). Retrofitting may include changes to the architecture, so the building owner must consider how the appearance of the building can attract economically advantaged tenants.

When it comes to health risks, there is a difference between taking risks yourself and taking risks on behalf of tenants. Some buildings are prone to high humidity levels and some buildings have high humidity levels due to user behaviour. Whether high humidity levels will cause health problems depends on how sensitive the building user is. Tenants may include persons ranging from healthy and robust persons in their best age to asthmatic babies, sensitive to health problems caused by damp buildings. User behaviour is just as wide-ranging. Normally the building owner will make sure his building can be rented out to a broad variety of people; therefore, he will have to choose a solution that is robust against user behaviour and sensitivity. He cannot be as specific in his risk assessment, as if he himself is the building user.

4.5 Prioritising solutions and risk assessment

In general, the building owner should chose a solution with a reasonable balance between the relevant parameters; e.g. architecture, building physics, durability, indoor climate, robustness of operation and costs. In practice, he should only chose a technically less safe solution if he gains more on other parameters by choosing that solution. He needs to assess the risk and compare it with the benefits of the solution. Assessing the risk includes:

- estimation of likelihood of defects (e.g. the probability of exceeding the level of acceptable relative humidity)
- consequences of defects (e.g. deterioration, chronic health problems or lower energy savings)
- costs of correcting defects (e.g. rehabilitation costs, discomfort and inconveniencies for users)

Especially the estimation of the risk of defects is difficult. The risk can be influenced e.g. by choice of material and extended quality assurance.

5. In practice – Danish guidelines and risk assessment

At present there are only few tools available to help the building owner to prioritise. In Denmark, guidelines describe principles for designing safe solutions. For new buildings, it is often possible to give examples of solutions that are generally considered to be safe for most uses. Where retrofitting is concerned, many factors are unknown and not everything is possible due to existing constructions. As a result, guidelines have to be pragmatic and describe not only the technically safest solutions, but also other possible solutions with a description of the prerequisites for each solution and a description of why the solution could be problematic and how the risk is diminished.

As retrofitting must cover many types of construction, guidelines (e.g. Møller, 2012) contain descriptions with thorough illustrations of typical situations and associated solutions as well as more general statements about solutions that are not standard or are compromises. However, there is no quantification of the moisture risk, because it depends very much on the specific case.

Today risk assessment is primarily based on guidelines and the experience of professionals. It is not mandatory to follow the guidelines, but if they are followed and a problem occurs anyway, the planner or contractor cannot be held responsible. This means that if the guidelines advise against specific solutions, these are de facto banned. Most professionals probably tend to recommend solutions that are on the safe side; it might be more costly, but in the end it can make life easier for the professional, the building user and the building owner.

6. Discussion - acceptable risks in the future?

It is not possible to construct new buildings or retrofit buildings without moisture risks. The question is what the acceptable risk is and how to assess the moisture risk.

6.1 Limit values

The reasons for not defining a moisture risk could be the difficulty in defining limit values based on scientific results. When it comes to defining the moisture limits to prevent degradation of materials, traditional experiments can show when degradation (e.g. corrosion or rot) starts, and materials-based limits can be found. However, when it concerns humidity causing indoor climate problems, it is unlikely that dose-response limits based on scientific knowledge will be defined in the near future. Specific knowledge of why moisture causes health problems is still lacking (WHO, 2010). Mould growth is strongly suspected of causing health problems. However, the connection between mould growth and moisture level is indirect, as materials, temperature and time are also decisive factors for mould growth (Sedlbauer, 2001). Another reason is the difficulty in measuring the exposure; should it be moisture or mould measurements? To this can be added the difficulty of finding suitable measuring methods.

One of the reasons why it is difficult to establish dose-response knowledge is that the dose-response limits are very personal; some people are more susceptible to health problems caused by dampness than others, e.g. children, asthmatics and allergic persons are especially sensitive (Danish National Board of Health, 2009 and WHO, 2010).

6.2 Moisture safety class

When IEA-ECBCS Annex 55 is finished, it could change moisture risk assessment from assessing a solution to be acceptable or non-acceptable, based mostly on experience, to a more refined risk assessment with a scientific approach where several parameters specific to a given case are taken into account. Until then, it could a realistic approach to introduce "moisture safety classes". Ideally, the classes should be defined by how many per cent of the population that, with normal use of the building, would not statistically experience health problems. Until more specific knowledge about dampness and health is available, a simpler less quantifiable method could be used.

An operational method for defining moisture safety classes could be to combine the hygrothermal load with the robustness of the solution against dampness and the resulting risk of mould growth. This would be equivalent to how structural design uses design loads and performance (load-bearing capacity).

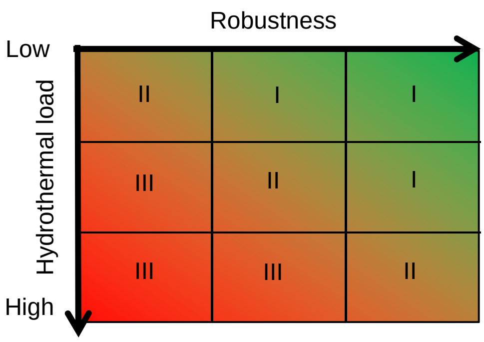


Figure 3: Example of how three moisture safety classes could be described based on robustness against dampness and hygrothermal load. Class I is the moisture safest.

In Figure 3, three moisture safety classes are proposed that are formed by subdividing robustness against moisture and moisture load into low, middle and high. Class I 'High Moisture Safety' is the best as it combines high robustness and low hygrothermal load and Class III 'Low Moisture Safety' is the worst as it combines low robustness and high loads. To reduce the number of classes, the two adjacent groups are also defined as Class I and

Class III respectively. Class II ‘Medium Moisture Safety’ covers situations in between Class I and Class III.

In this way, it would be realised that in certain buildings some people will have difficulties in obtaining an indoor climate that does not cause them problems. People who know that they are sensitive to higher humidity levels could choose to live in buildings with a High Moisture Safety classification. The costs would probably be higher, but so would the safety. This could be a way to accept e.g. interior insulation in older buildings; the moisture risk would be higher, but only people who are less prone to moisture-related indoor climate problems would choose to use these buildings. This could be an argument for the building owner who uses the building himself, and who has an idea of whether he or his family are prone to moisture-related problems. This solution would not be possible for office buildings.

The “moisture safety classes” could also be used the other way around; buildings with a low moisture safety classification can be used by more people, if the moisture level is kept low. This means low moisture production, no cold areas and good ventilation. In practice, this would be the same recommendations as used today when people experience moisture problems in existing buildings. This illustrates that today’s buildings are not built for everybody; their moisture safety class is just not defined.

6.3 Ban or explain risky solutions

As long as there are no moisture safety classes or methods of risk assessment, risky solutions must be handled in another way. The simple approach is to ban solutions that are risky, but on what grounds can a solution be judged to be risky? Another way is to guide building owners so that they are themselves able to make an informed choice and prioritise between several solutions. To assess whether a solution is risky from a moisture point of view, it is necessary to understand how the building physics of the solution works. Guidelines with different solutions must therefore not only describe how the retrofitting can be executed but must also explain the prerequisites and pitfalls of the solution.

Interior insulation is an example of a solution that is judged to be risky by many professionals, (Møller, 2012); the pitfalls are known (see section 3.1) and have been pointed out for years. Nevertheless, new examples of interior insulation with moisture problems still turn up, sometimes because neither the planner nor the contractor was aware of the problem, in other cases problems occur despite various precautions. Unfortunately, it is not known how often the solution fails and the reasons for failing are not always analysed. However, it illustrates how difficult it is to make it right.

Maybe interior insulation should be banned. In some cases, this would mean that additional insulation would in practice be impossible, thus blocking retrofitting of buildings to improve their energy efficiency. Instead, the awareness of the problem can be strengthened by describing the problem and emphasising that the solution is known to result in moisture problems and is therefore judged to be risky.

7. Conclusion

In an ideal world, all buildings have an indoor climate after retrofitting with no restrictions on moisture and temperature conditions. However, this would mean strict regulations regarding what solutions may be used. Some solutions would be too risky and should therefore be banned with the result that some buildings would not be retrofitted. This scenario would counter the need for lower energy consumption in existing buildings and would be very costly and therefore unrealistic. On the other hand, no regulations, where building owners are to decide what constitutes an acceptable risk, can result in solutions where only few people can use the building without developing health problems or where the building's use is very limited. This is especially problematic when buildings are rented out.

Instead, moisture safety classes should be defined. The classes could be based on a combination of hygrothermal load and robustness against dampness. In this way, building owners and users know the limits of the building. However, to define moisture safety classes, more knowledge about moisture is needed regarding:

- how often do constructions that are generally judged to be risky from a moisture point of view actually cause moisture problems
- how moisture or mould exposure should be determined including appropriate measurement techniques.
- dose-response relationship between moisture level and health effects, although a direct connection is probably very individual
- reliability-based modelling of building physics including parameters for moisture/mould loads, resistance, consequences of defects and acceptance criteria

Until this becomes known, society must operate with a combination of information on why some solutions are more risky than others and descriptions on how the risk is reduced. In Denmark, guidelines describe the best technical solutions as well as more risky ones; no solutions are banned, but some are judged to be risky. The idea is to help the building owner to decide what solution is the best in his particular case, because the safest technical solution is not always the best solution.

References

CEN (2002): *Eurocode – Basis of Design*, CEN/EN 1990:2002, Eurocode 0.

de Place Hansen (editor) (2010) *Guidelines on Building Regulations 2010*. SBi guidelines 230, Hørsholm, Danish Building Research Institute, Denmark

Danish Enterprise and Construction Authority (2010) *Building Regulations 2010*, Danish Enterprise and Construction Authority, Copenhagen, Denmark

Danish Ministry of Refugee, Immigration and Integration Affairs, 2004, *Regeringens strategi mod ghettoisering* (author's translation from Danish: the Government's strategy against ghettoisation), (available online: https://www.nyidanmark.dk/bibliotek/publikationer/regeringsinitiativer/2004/regpub_ghettoisering/ghettoisering.pdf [accessed 31.10.2012])

Danish National Board of Health (2009) *Personers ophold I bygninger med fugt og skimmelsvamp Anbefalinger for sundhedsfaglig rådgivning* (author's translation from Danish: Persons staying in buildings with damp and mould). Recommendations for health advice) Sundhedsstyrelsen, Copenhagen, Denmark

IEA-ECBCS (2012): Annex 55 Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance & Cost (RAP-RETRO) http://www.ecbcs.org/annexes/annex55.htm [accessed 22.11.2012]

European Parliament (2010) "*Directive* 2010/31/EU *of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings on the energy performance of buildings",* Official Journal of the European Communities (available online: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L: 2010:153:0013:0035:EN:PDF [accessed 31.10.2012])

European Standard (2001) *Hygrothemal performance of building components and building elements – Internal surface temperature to avoid critical surface humidity an interstitial condensation - Calculation methods*. EN ISO 12788. European Standard, Brussels, Belgium

Knudsen H N, Jensen O M & Kristensen L (2012) "Occupant satisfaction with new low-energy houses". *Proceedings of Healthy Buildings 2012*, 8 - 12 July 2012, Brisbane, Australia

Morelli M, Nielsen, T R, Scheffler G A & Svendsen S (2010) "Internal Insulation of Masonry Walls with Wooden Floor Beams in Northern Humid Climate", *Proceedings of Thermal Performance of the Exterior Envelopes of Whole Buildings XI,* December 5-9., Clearwater Beach, Florida.

Møller E B (2012) *Efterisolering af småhuse – byggetekniske løsninger* (author's translation from Danish: Post insulation of single family houses – constructional solutions). SBi guidelines 240, Hørsholm, Danish Building Research Institute, Denmark

Møller E B, de Place Hansen E J & Brandt E (2011) "Performance and Durability of External Post-Insulation and Added Roof Constructions", *Proceedings of the XII International Conference on Durability of Building Materials and Components,* April 12th-15th, Porto, Portugal.

Pietrzyk K.& Hagentoft C-E (2008) "Reliability analysis in building physics design", *Building and Environment*, Vol.43.4, p. 558-568.

Sedlbauer K (2001) *Prediction of mould fungus formation on the surface of and inside building components.* Ph.D. Thesis, University of Stuttgart, Germany

WHO (2010) *WHO guidelines for indoor air quality: dampness and mould*, WHO, Copenhagen, Denmark

Wittchen K B (2004) *Vurdering af potentialet for varmebesparelser i eksisterende boliger* (author's translation from Danish: Evaluation of the potential for heat reduction in existing dwellings) By og Byg Dokumentation 057, Hørsholm, Denmark