Tampere University

PETRI ANNILA

Detecting Moisture and Mould Damage in Finnish Public Buildings

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ACADEMIC DISSERTATION
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Responsible supervisor and Custos	Adjunct Professor Jukka Lahdensivu Tampere University Finland	
Supervisor	Professor Matti Pentti Tampere University Finland	
Pre-examiners	Professor Targo Kalamees Tallinn University of Technology Estonia	Research Director Ruut Peuhkuri Aalborg University Denmark
Opponent	Senior Vice President Miimu Airaksinen SRV Oyj Finland	

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ABSTRACT

Indoor air quality problems and moisture and mould damage in different structures are among biggest issues in the Finnish building stock, especially in public buildings. These are all global problems but most significant indoor air impurity varies by country. The impact of indoor air quality problems affects many people, so more efficient procedures to detect indoor air impurities are needed. When trying to create a healthy indoor envi-ronment, it is necessary to take into account all possible indoor air impurities. However, in Finland the presence of moisture in structures, and moisture and mould damage are common reasons for indoor air quality problems, so the examination of such damage separately from other indoor air quality issues is also necessary.

This thesis focuses on moisture and mould damage in structures in Finnish public build-ings. The main objective is to increase our knowledge of moisture and mould damage to these buildings. One of the key factors is to identify how structures, the age of buildings or building materials have affected moisture and mould damage. It is also important to analyse how such damage has been detected. This knowledge will help us to develop new procedures and methods to improve building maintenance and help us to prevent damage in future. The research data consist of a moisture and mould damage database comprising reports of moisture performance assessments. The database has been ex-amined by statistical analysis and case studies.

This thesis points out the structures where moisture and mould damage are most com-mon and where the detection of damage is most difficult. In Finnish public buildings, damage is common in structures with soil contact, but that kind of damage can usually be detected quite easily. Detecting damage is most difficult in structures, which consist of many layers of different materials. Visual inspections and moisture mappings with a surface moisture detector are useful tools to evaluate the condition of many buildings. The statistical data, however, cannot be the only data for renovating individual buildings, so thorough moisture performance assessments are still needed.

Keywords: moisture and mould damage, condition investigation, moisture performance assessment, indoor air quality, service life

PREFACE

The fundamental purpose was to examine moisture and mould damage to Finnish pub-lic buildings and produce data, which can be utilised to develop more efficient damage detection methods and tools to prevent and minimise the negative effects of moisture and mould damage. The study was conducted in the Renovation and Service Life Engi-neering of Structures research group at Tampere University (Tampere University of Technology until 2018) between 2013 and 2019.

From support and guidance, I am grateful to my supervisors Adjunct Professor Jukka Lahdensivu and Professor Matti Pentti. Matti's encouragement and the inspiring topic were the motivation to embark on this thesis. Jukka's confidence helped me get all the way to the finish. Both of them were equally important in achieving the results.

I wish to thank Professor Targo Kalamees and Ruut Peuhkuri Ph.D. for their valuable pre-examinations of my thesis. Their comments improved the outcome and made it easier to understand.

Without a fertile working environment, high-quality results cannot be achieved, so thanks also belong to co-authors Toni Pakkala M.Sc., Matti Hellemaa B.Sc., Jommi Suonketo M.Sc., Professor Juha Vinha and the entire Renovation and Service Life En-gineering of Structures research group.

The author is grateful for the financial support he received. Without it, this journey would not have been possible. Special thanks go to Kiinko Real Estate Education, the KAUTE Foundation, the Jenny and Antti Wihuri Foundation, the Yrjö and Senja Koivunen Foun-dation and to all companies and municipalities that participated in the COMBI research project from 2015 to 2018.

When one project ends, the whole world is still open. My deepest gratitude is reserved for my loved ones. You deserve a healthy home.

Tampere 24.4.2022

Petri Annila

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TERMINOLOGY

Hidden damage

Hidden damage is moisture or mould damage located inside the structure that cannot be detected without dismantling the structure or its material layers.

Moisture and mould damage

A structure or building material is moisture- and mould-damaged when at least one of the definitions is fulfilled. Usually, moisture damage and mould damage occur simul-taneously. From the perspective of the whole building or structure, it is often not necessary to specify whether it is moisture or mould damage so, in moisture performance as-sessments, it is usually just called moisture and mould dam-age. For point-size damage, it is relevant to divide moisture and mould damage into two categories.

Moisture damage

A structure or building material is moisture-damaged when its moisture content exceeds critical moisture conditions and when this moisture impairs or weakens the properties of ma-terial. Resistance to moisture varies between building mate-rials and there are no exact values for different materials or structures. In most sensitive materials, the typical limit value at normal indoor air temperatures is about 80% relative hu-midity according to mould growth models. However, how long the building material or structure has been affected by moisture also has an impact on the scale of moisture dam-age.

Moisture performance assessment

This is a condition inspection or assessment, the main aim of which is to determine the condition of a building in terms of indoor air quality, and moisture and mould damage to struc-tures. The assessment includes, for example, visual obser-vations, the dismantling of structures, sampling and multiple different measurements.

Mould damage

Mould damage develops when continuous moisture stress leads to microbial growth in building material or a structure. Sensitivity to mould damage varies between building materi-als. The moisture content of a material could fall below the critical level and mould growth may stop, but it can be reac-tivated when the moisture stress again increases. Old dead microbe growth is also counted as an indoor air impurity in Finland.

Mould growth models

Calculation models that can be utilised when estimating pos-sibilities or the time period needed for mould growth in a ma-terial or structure in certain or changing temperature- and moisture conditions. These models can also be utilised when determining critical moisture level in or moisture load on dif-ferent structures.

Risk structure

A risk structure is one where moisture or mould damage are statistically more common than in normal structures. The moisture and mould damage in risk structures are usually hidden, which is why damage will usually have been devel-oping to a severe level before detection. The classification of risk structure is usually done after decades, once it has been realised that the used structures and building materials are too sensitive to moisture and mould damage in current con-ditions.

Service life

The period of time when a building material or whole struc-ture exceeds the performance requirements set for it. Now-adays, service life guides structural planning but, in old build-ing stock, it is different. In older buildings, service life predic-tions are based on practical experiences of the current build-ing stock.

Water damage

Damage to building material or structures as a consequence of pipe leaks or similar accidents. Water damage is a type of moisture damage.

Visual inspection

Visual inspection is a walk-through assessment or condition inspection which includes visual inspections made by condi-tion inspector and measurements with surface moisture de-tector.

LIST OF SYMBOLS AND ABBREVIATIONS

CO	carbon monoxide
DG18	dischloran 18% glycerol agar
$E_{80\%}$	error term, which include 80% of examined buildings
IAQ	indoor air quality
MEA	2% malt extract agar
MSAH	Ministry of Social Affairs and Health
N_{mmd}	an estimated number of moisture- and mould-damaged structures
NO_2	nitrogen dioxide
PAH	polycyclic aromatic hydrocarbon
R^2	coefficient of determination
TYG	tryptone glucose yeast agar
VOC	volatile organic compound
WDR	wind-driven rain
WHO	World Health Organization
y	age of the building (years)

LIST OF PUBLICATIONS

I. Annila, P. J., Lahdensivu, J., Suonketo, J. & Pentti, M. 2016. Practical Experiences from Several Moisture Performance Assessments. J.M.P.Q. Delgado (ed.), Recent Developments in Building Diagnosis Techniques, Building Pathology and Rehabilitation 5, pp. 1-20.

II. Annila, P. J., Hellemaa, M., Pakkala, T. A., Lahdensivu, J., Suonketo, J. & Pentti, M. 2017. Extent of moisture and mould damage in structures of public buildings. Case Studies in Construction Materials 6 (2017) 103-108.

III. Annila, P. J., Lahdensivu, J., Suonketo, J., Pentti, M. & Vinha, J. 2018. Need to repair moisture- and mould damage in different structures in Finnish public buildings. Journal of Building Engineering 16 (2018) 72-78.

IV. Annila, P. J. & Lahdensivu, J. 2020. Reliability of the detection of moisture and mould damage in visual inspections. 12th Nordic Symposium on Building Physics (NSB 2020) E3S Web Conf. Volume 172, 2020. 7 p.

AUTHOR'S CONTRIBUTION

Annila was the responsible author of all the publications, set the research questions and was responsible for the results and drawing conclusions. The following researchers also participated in writing articles and executing studies:

Lahdensivu and Pentti supervised the research and participated in the internal review of manuscripts.

Suonketo and Pentti were responsible researchers in a significant part of the original moisture performance assessments used in the research material, especially in articles I, II and III.

Hellemaa was responsible for the calculator examination of research results and also participated in the analysis of results in Article II. Pakkala participated in analysing the results in Article II.

Vinha was the researcher responsible for the COMBI project and participated in setting the research questions in Article III.

1 INTRODUCTION

1.1 Aging of building stock in Finland

A considerable proportion of the building stock in Finland was built in period of reconstruction immediately after World War II and during the 1970s and 1980s as presented in Figure 1 (OSF, 2019).

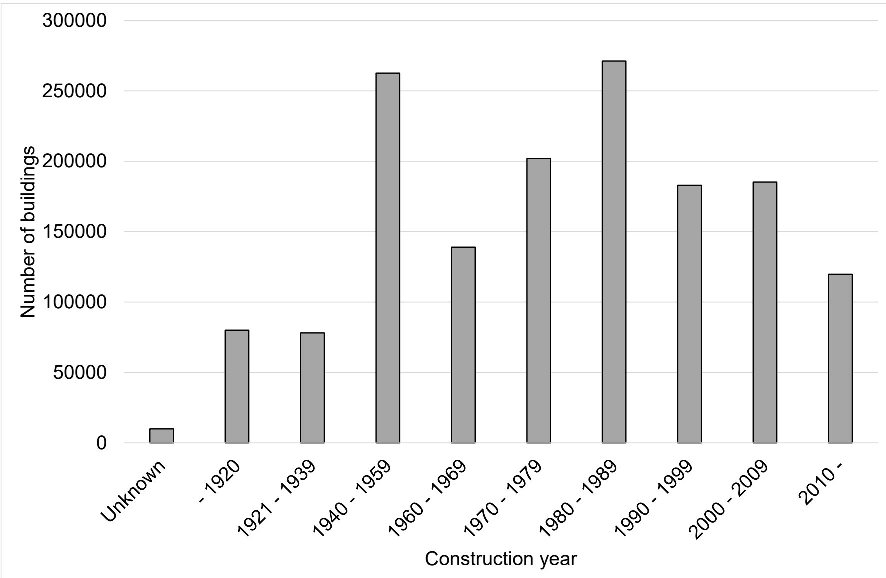


Figure 1. The number of new buildings in Finland and the construction year distribution of Finnish building stock.

Compared to many other European countries, the Finnish building stock is thus relatively young. The data in Figure 1 also include buildings in which the year of construction is unknown. It is probable that this category mostly includes old buildings, which is why it is located first on the timeline in Figure 1. It should be noted that time periods in different age groups are not similar; for example, the age group '*1940-1959*' includes two decades whilst newer age groups include only one decade. However, this is typical classification when examining the building stock in Finland.

The Finnish building stock was renewed slowly. In recent years, the share of annual new buildings has been about 1% of the entire building stock in Finland, but the demolition rate is even lower; only 0.25% if measured as the number of buildings and 0.15% if measured as floor area (Huuhka & Lahdensivu 2016). If a similar trend continues, these values mean that current building stock will remain in use for many decades before demolition.

The total number of public buildings has increased in quite a linear way as presented in Figure 2. The figure shows how the total number of public buildings has developed and how the number of different buildings has increased the data are based on the publication Vainio et al. 2006.

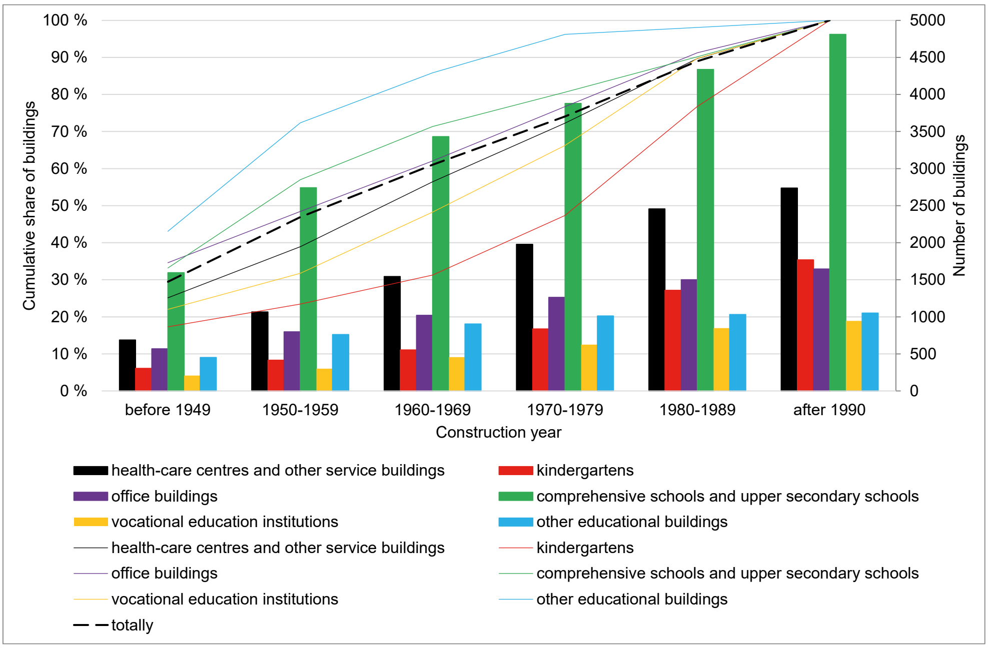


Figure 2. The cumulative age distribution and number of public buildings in Finland. The data are based on numbers of buildings.

The almost linear growth in the number of public buildings is partly a consequence of the rapidly increasing average size of buildings over the decades. The average size of buildings in different decades is presented in Table 1. All values in this table are 1,000 m²/building. The data in figures 2 and 3, and Table 1 are based on previous publications about public buildings in Finland (Vainio et al. 2006) and they show the situation in 2005.

Table 1. The average size of public buildings in Finland. All values are 1,000 m²/building.

	Construction year					
	before 1949	1950-1959	1960-1969	1970-1979	1980-1989	after 1990
health-care centres and other service buildings	1.8	1.9	1.9	2.2	2.2	2.2
kindergartens	0.5	0.5	0.5	0.6	0.6	0.6
office buildings	1.0	1.0	1.2	1.3	1.4	1.4
comprehensive schools and upper secondary schools	1.1	1.4	1.6	1.7	1.7	1.7
vocational education institutions	2.2	2.8	3.4	3.5	3.3	3.3
other educational buildings	0.5	0.8	0.9	1.0	1.0	1.0

When the data is analysed from the perspective of floor area as in Figure 3, the age distribution of public buildings is quite similar to the entire building stock in Finland as presented in Figures 1 and 3 Population growth and large age cohorts in Finland at the end of 1940s is reflected in the age distribution of public buildings. At first, there was a need for school buildings during the 1950s and 1960s and after that a need for kindergartens and office buildings.

The stock of Finnish public building is aging, and a significant number of existing public buildings will need refurbishment in the near future as presented in Figure 4. The figure shows the share of refurbished public buildings in Finland. The figure is based on the study Vainio et al. (2006). The data include all buildings, which are owned by municipalities or public corporations. The share of refurbished buildings is calculated according to volume of buildings. A little over half the buildings built before the 1970s had been renovated by 2005.

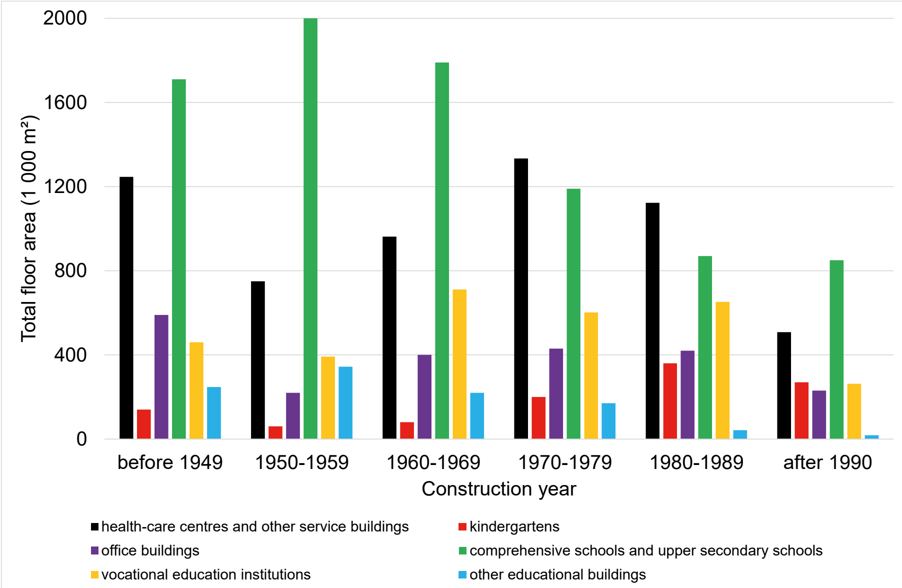


Figure 3. The age distribution of public buildings: data based on the total floor area of buildings.

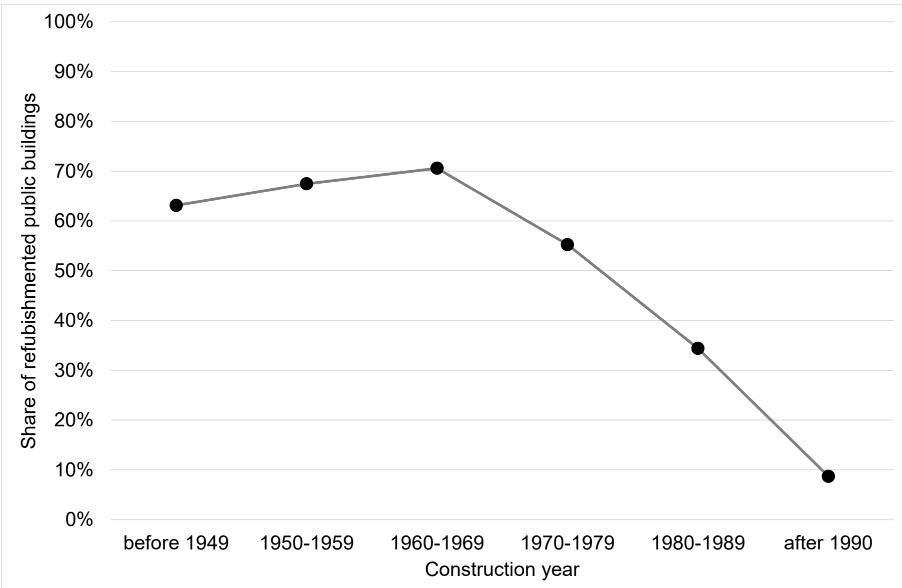


Figure 4. Share of refurbished public buildings in Finland according to age of the buildings. The share is based on volume of buildings and the data are from 2005.

The purpose of buildings affects how large a share of them are refurbished. In Figure 5 the data are arranged according to the purpose of the building (Vainio et al.

2006). The figure includes those building types, which are presented in research material, not all public buildings as in Figure 4. The share of refurbished buildings varies between 21-63% in these six categories. It was lowest in ‘kindergartens’ and ‘other educational buildings’ in 2005. A refurbished building in the publication Vainio et al. (2006) means one where the refurbishment or renovation project was so thorough that it needed a building permit.

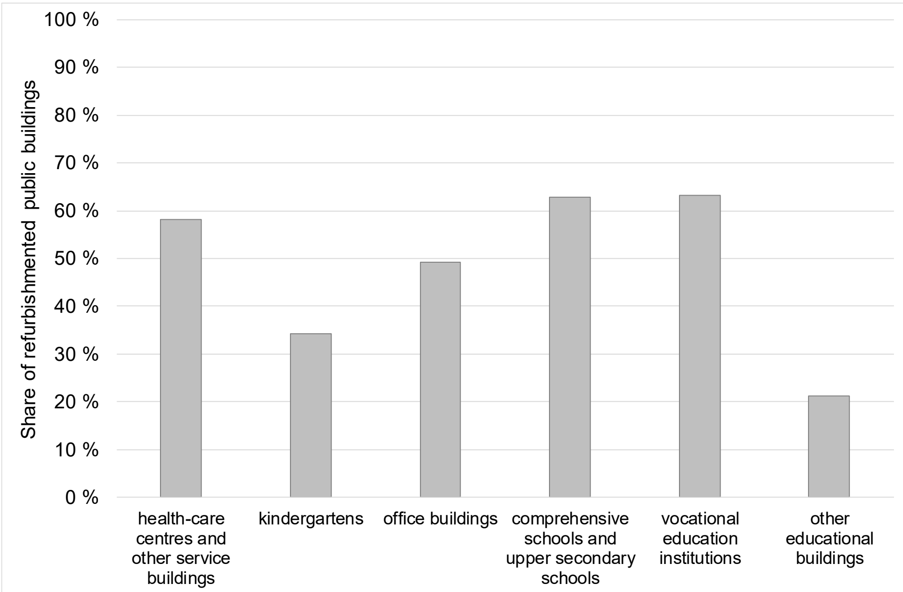


Figure 5. Share of refurbished public buildings in Finland according to purpose of use. The share is based on volume of buildings and the data are from 2005.

The typical service life of different structures, building materials and technical systems varied between 30 and 50 years in Finland, depending on the local stresses and properties of the building (RT 18-10922, 2008). In some buildings, the need for repair may already appear during first few years after construction and, in some buildings, it may be reasonable to postpone refurbishment even for a building 50 years old whose estimated service life has been exceeded.

Service life planning is quite a new part of the design process of buildings and structures in Finland. In the current building stock, therefore, service life estimations are mainly based on practical experiences from previous decades, not planned service life periods before construction. These typical service life periods, 30-50 years, mean that buildings from the 1960s, 1970s and 1980s are now under refurbishment. However, as can be note from Figure 4, older buildings are also still awaiting comprehensive refurbishment projects.

1.2 Refurbishment of existing buildings in Finland

In Finland, the value of the new construction and refurbishment of existing buildings has been at a similar level in recent years. In 2019, the values were €15.3 billion and €12.9 billion, respectively. These two main sections could be further divided into residential buildings and other buildings as presented in Figure 6 (Riihimäki et al. 2019).

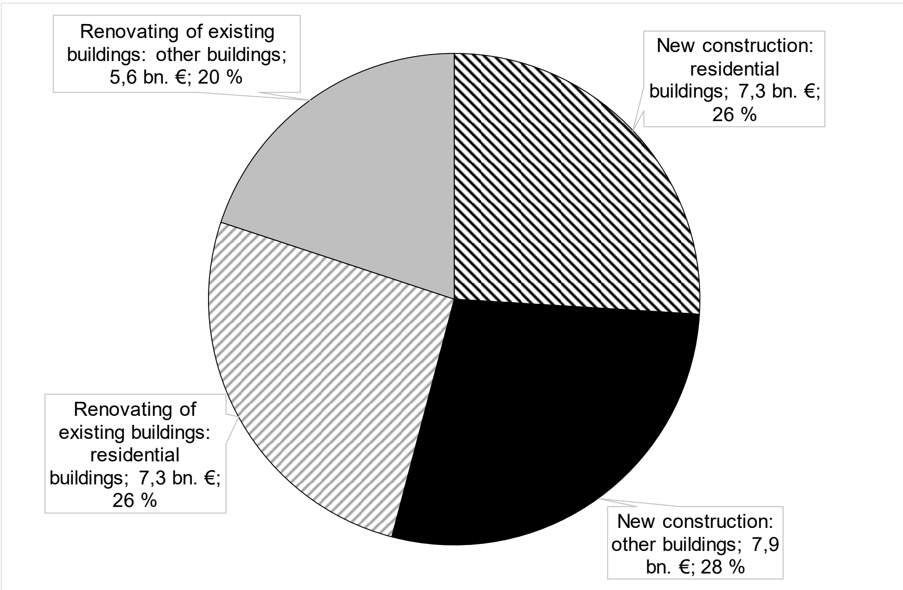


Figure 6. Value of construction in Finland 2019 (Riihimäki et al. 2019)

The Finnish building stock is only slowly renewed: between 2000 and 2012, the demolition rate was on average 0.25% per year measured as the number of buildings, and 0.15% measured as floor area (Huuhka & Lahdensivu, 2016). These demolition rates mean that most buildings are refurbished to continue their service life, or that refurbishment projects are postponed even though the optimal refurbishment time is at hand or already exceeded. Altogether, based on values from recent years, a large proportion of public buildings will be renovated in the future and their service life will continue.

The refurbishment market consists of many different refurbishment and renovation projects. A couple of typical examples in Finland at present are façade renovations, plumbing replacement, refurbishment due to the end of the service life of different structures, and changes in indoor spaces or purposes of buildings.

To summarise, the refurbishment of the Finnish building stock is necessary, and in many cases these projects also solve indoor air quality problems, and moisture and mould damage to structures, especially in public buildings.

1.3 Moisture and mould damage to public buildings in Finland

Moisture and mould damage have been noticed as significant indoor air quality problems in Finland since the 1990s. These indoor air quality and moisture and mould damage issues have not yet been resolved, which is why the Finnish Parliament has launched a study (Reijula et al. 2016) focusing on moisture and mould damage to the Finnish building stock. This study is a conclusion from many scientific studies and national reports from previous years. It reveals that moisture and mould damage occur in 2.5-26% of Finnish buildings depending on the building type (Reijula et al. 2016). In public buildings, the incidences of significant moisture and mould damage are as follows:

- Schools and kindergartens 12-18%
- Health care facilities 20-26%.

It is estimated that the total number of occupants in these moisture- and mould-damaged buildings are 172,000-259,200 (3.1-4.7% of the Finnish population) and 36,000-46,800 0.7-0.8% of Finnish population) respectively (Reijula et al. 2016).

At the rare cases moisture and mould damage are the only indoor air quality issue in building. Other common indoor air quality issues in Finland are, for example, the low relative humidity of indoor air, lack of ventilation, dust and mineral wool fibres (Reijula et al. 2016). Therefore, all possible indoor air impurities should be taken into account in moisture performance- or indoor air quality assessments before refurbishment projects.

It is estimated that problems related to moisture and mould damage will increase in Finland as a consequence of climate change (Tuomenvirta et al. 2018). It is estimated that climate change is increasing the moisture stress on building envelopes. These stresses are:

- rise of outdoor temperatures
- increases in annual rainfall
- increases in cloudiness
- increases in relative humidity of outdoor air
- increases in windiness.

These factors increase the risk of moisture or mould damage to building envelopes (Vinha et al. 2013) and moreover, it is probable that higher risk will increase the cost of solving the issues and set more technical challenges to preventing damage in the future. Increases in annual rainfall and the impairment of drying conditions also increases moisture stress from the ground.

The Prime Minister's Office is facilitating the *Terveet tilat 2028* (Healthy Indoor Spaces 2028) programme in Finland. The main aims are to ensure healthy indoor air quality in public buildings and develop methods for treating health issues, which are a consequence of indoor air quality problems. Seven starting points have been set to this programme. Point one is to launch actions to identify the condition of buildings and develop an operational model for healthy indoor spaces (Prime Minister's Office, 2020). This aim is based on fact that there is not enough and precise knowledge about the condition of buildings in Finland, so the subject of the thesis is topical.

1.4 Research objectives and questions

This study focuses on moisture- and mould-damaged public buildings and their damaged structures in Finland. The research material includes buildings built between 1840 and 1998. The data includes schools, kindergartens, office buildings and health care facilities.

The objective of the study is to develop condition management for public buildings from the perspective of moisture and mould damage to structures, and also to minimise their negative effects on indoor air quality conditions and the long-term durability of buildings. The study considers how to use statistical data from previous damaged buildings to prevent damage in future, and, moreover, how suitable tool visual inspection and moisture mapping with surface moisture detectors are for detecting damage.

The following research questions were addressed:

1) What is the extent of moisture and mould damage in Finnish public buildings? Are there differences between the structures?
2) How has the age of buildings or main building materials affected moisture and mould damage?
3) How have moisture and mould damage been detected in thorough moisture performance assessments?

4) How reliable is visual inspection and moisture mapping compared to moisture performance assessment? In which structures are moisture and mould damage most often hidden?

2 BACKGROUND

2.1 Indoor air quality problems

Indoor air quality (IAQ) and indoor environment problems are complex. There are many different impurities and factors that could decrease indoor air quality and lead to indoor air quality problems. The final issues often also arise from a combination of several impurities and factors. The most common issues vary between, for example, countries, weather zones, and the location of buildings and also depend on the basic features of buildings.

The World Health Organization (WHO) has recommended indoor air quality guidelines for the following chemical indoor air pollutants (WHO, 2010):

- benzene (C_6H_6)
- carbon monoxide (CO)
- formaldehyde (CH_2O)
- nitrogen dioxide (NO_2)
- naphthalene ($C_{10}H_8$)
- polycyclic aromatic hydrocarbons (PAHs)
- radon (Rn)
- tetra- and tri-chloroethylene (C_2Cl_4 and C_2HCl_3).

The WHO has also recognised microbial pollution as a key element of indoor air pollution. Microbial pollution is a consequence of hundreds of species of bacteria and fungi growing indoors (WHO, 2009).

Almost the same list of indoor air impurities is also followed in Finland. In residential buildings and other living areas, the Finnish Ministry of Social Affair and Health has set limit values in the following areas (Ministry of Social Affairs and Health, 2015):

- indoor air humidity
- temperature and air velocity
- tap water temperature
- ventilation
- action limits for noise
- volatile organic compounds (VOC)

- formaldehyde
- carbon monoxide
- tobacco smoke
- particulate pollutants
- microbes.

The limit values for these impurities are applied in the monitoring of the health-related conditions of housing and other residential buildings (Ministry of Social Affairs and Health, 2015). In terms of microbes, the following factors exceed the limit values:

- unrepaired moisture or mould damage
- microbe growth detected with sensory or material samples
    - microbe growth is usually found on the interior surfaces of structures. If the location is on a layer of thermal insulation or inside a structure, lack of airtightness, air flows and pressure differences enable indoor air contamination
    - thermal insulation must not be in contact with soil or outdoor air.

The primary detection method for mould growth is material samples cultivated in a laboratory. Mould growth may also be detected with indoor air samples or samples from surfaces (Ministry of Social Affairs and Health, 2015).

These WHO or Finnish lists of indoor air impurities are not comprehensive, and many other pollutants and indoor air quality parameters and their effects have been examined in scientific studies. However, in Finland moisture and mould damage have been found to be significant factors in diminishing indoor air quality (Reijula et al. 2012). Moisture and mould damage are also common topics in scientific studies in many countries as Bornehag et al. (2001 and 2004) point out. Altogether, moisture and mould damage can be identified as a significant factor that negatively affects indoor air quality, so examination separately from other indoor air impurities is also necessary.

Moisture is also present or one affecting factor in the deterioration of almost all building materials. It causes, for example, the corrosion of steel and the deterioration of concrete structures and wooden materials. Moisture may also increase the chemical emissions of different building materials, so moisture performance management and building physics are key factors in service life engineering and securing healthy indoor environments in Finland and worldwide.

2.2 Moisture and mould damage to the existing building stock

The extent of moisture and mould damage has been a topic of only some scientific studies. It may be also a common topic also in national reports and surveys, but these may not be published in scientific journals or in English. Condition investigations are mainly conducted on individual buildings, so the property owner may be the only one receiving information on moisture and mould damage to his/her building. Therefore, this data or knowledge does not end up in public registers or reports in Finland.

Table 2 presents a summary of scientific studies. It is based on the publication Annila et al. 2018 (Article III). Moisture or mould damage has occurred in 0-80% of the surveyed buildings in these studies listed in Table 2. It should be noted that the definition of moisture and mould damage and the research methods used vary between the studies, so the share of damaged buildings is not fully comparable.

Table 2. Extent of moisture and mould damage in a few scientific studies (Annila et al. 2018; Article III).

Reference	Research material	Result
Lawton et al., 1998	59 homes in Canada	The share of moisture damaged structures was between 0-77%.
Nevalainen et al., 1998	450 houses in Finland	Trained civil engineers detected current or previous moisture faults in over 80% of buildings.
Howden-Chapman et al., 2005	613 households in New Zealand	35% of occupants from these houses reported visible mould in one or more of their rooms.
Haas et al., 2007	66 households in Austria	In on-site inspections, visible mould growth was found in 56% of the apartments.
Salonen et al., 2007	77 office buildings in Finland	Experienced construction engineers found dampness or visible mould damage in 44% of buildings.
Holme et al., 2008	205 homes in Norway	Professional inspectors detected one or more visible indicators of a moisture problems in 50% of the buildings.
Haverinen-Shaughnessy et al., 2012	59 school buildings in Finland, 85 in Spain and 92 in the Netherlands.	Signs of damp or mould were detected in 24% of Finnish schools, 47% of Spanish schools and 43% of Dutch schools.

Nevalainen et al. (1998) focus on Finnish houses from the 1950s to the 1980s. Structures were divided only into three categories: roof, basement and wall. The occurrence of moisture damage was highest in buildings from the 1970s. The most commonly damaged structure in the 1950s, 60s and 70s was the roof. In buildings from the 1980s, the most commonly damaged structures were the walls.

Howden-Chapman et al. (2005) focuses on households in New Zealand. Prevalence of mould reported in any room of the house was highest (40.1%) in '22-40 years' old buildings. In age groups '10-22 years' old and 'over 44 years' old the prevalence is almost the same: 37.9 and 37.6% in respectively order. Prevalence was lowest, 17.5%, in new buildings ('below 10 years').

Haas et al. (2007) detected visible mould growth in 56% of the examined apartments in Austria. In 84% of the apartments, mould growth was concentrated only in a small area (categories 'dotted spots' and '< 1 m²'). Only in 16% of apartments did the area of mould growth exceed 1 m². The study focuses on households in Austria.

Holme et al. (2008) observed in Norway that visible signs of a moisture problem were most common in basements: such signs were noticed in 65% of basements. Visible moisture signs were detected only in 5-21% of the other rooms (children's bedrooms, living rooms and bathrooms). The most common moisture indicator in basements was leakage from the ground.

Haverinen-Shaughnessy et al. (2012) compared school buildings in Finland, Spain and the Netherlands. The most common suggested moisture source was 'water from outside'. This was suggested in 22% of cases in Finland, 34% in Spain and 21% in the Netherlands. The study points out that moisture signs were most common in the oldest buildings ('< 1970').

To summarise these studies (Nevalainen et al. 1998, Howden-Chapman et al. 2005, Haas et al. 2007, Holme et al. 2008 and Haverinen-Shaughnessy et al. 2012) the following conclusions can be drawn:

- the age of building is strongly related to the amount of damage, but the oldest buildings are not always the most damaged
- damage is more common in basements and envelope structures
- damage is more likely to be point-sized than widespread
- the most common cause for damage is 'water from outside', which also includes moisture stresses from soil.

However, as mentioned, the research material and research methods vary between studies, and the definition of moisture and mould damage varies. The condition of buildings based on quite light condition inspections, surveys or estimates does not provide exact data compared to comprehensive moisture performance assessments. In conclusion, it can be noted that, when the number of examined building rises, the accuracy and comprehensiveness of condition inspections decrease. When a condition inspection is at its most comprehensive, the amount of research material is limited, so the effect of a single building on the average condition of the buildings is substantial. The results of the study are therefore heavily dependent on which buildings are inspected. Lack of knowledge of the condition of public buildings has been identified as a problem in Finland, so data collection of the condition of public buildings has been set as one of the main goals in the Healthy Indoor Spaces 2028 programme in Finland, facilitated by Prime Minister's Office (Prime Minister's Office, 2020).

2.3 Moisture stress

2.3.1 Moisture sources

Moisture stress and moisture load affect buildings from several sources. From a Finnish perspective, Leivo et al. (1998, p. 21) have divided these sources into eight main categories, which are:

- precipitation, especially wind-driven rain (WDR)
- surface water
- outdoor relative humidity
- moisture of the soil
- moisture content of structures
- domestic water
- indoor relative humidity
- pipe leaks.

Almost similar sources are mentioned in other references. Hagentoft (2003, p. 87-88) has divided moisture sources into the following five groups:

- indoor and outdoor air humidity
- construction dampness (building moisture)
- precipitation
- water leakage
- moisture in the ground.

A Finnish guideline (RIL 255-1-2014) presents the key elements of moisture stress, which should be take into account in the physical analyses of buildings in the Finnish climate. Types of moisture stress are considered separately for every structure and can be divided into the above sources.

2.3.2 Moisture sources of different structures

Moisture excess to indoor air

Ilomets et al. (2018) drew conclusions from scientific studies and seven of these indicated moisture excess (Kalamees et al. 2006; Janssens and Vandepitte 2006; Zhang et al. 2007; Francisco and Rose 2010; Geving and Holme 2011; Tariku and Simpson 2014; and Bagge et al. 2014). The conclusion of Ilomets et al. was that average moisture excess in indoor spaces varies between 1.6 and 6.1 g/m³. Ilomets et al. (2018) also studied 237 dwellings in Estonia and the average moisture excess value determined was 2.8 g/m³ during cold periods. This moisture excess is a consequence of normal living. The average moisture excess was highest (+2.8 g/m³) during cold periods (outdoor temperature below +5 °C) and lowest (+0,3 g/m³) during warm periods (outdoor temperature over +20 °C) (Ilomets et al. 2018).

Moisture excess, the moisture content of indoor air and moisture movements should be studied in building physics analyses so as not to lead to, for example, condensation or other moisture or mould damage. This applies to all structures and especially envelopes.

External walls and uppermost floors

The direction of moisture transfer by diffusion in external walls and uppermost floors is usually from inside to outside in Finland and other cold regions during the heating season if indoor temperature is normal (+21 °C). This is a consequence of moisture excess in indoor spaces and the low moisture content of outdoor air, so vapour barriers are located inside thermal insulation layers in Finnish structures. However, if long-term cooling is used in these buildings during hot and humid days, the direction of moisture flow may change, which may cause problems.

During the heating seasons and cold periods, high indoor moisture excess does not automatically mean high indoor air relative humidity. Table 3 presents the level of indoor air relative humidity in different weather zones with a moisture excess of 2.8 g/m³. Weather zones and outdoor temperatures are based on old building codes in Finland (RakMK D3, 2012). These weather zones are presented in Figure 7. Outdoor temperatures are average temperatures in January. Outdoor relative humidity is 100%RH. The value of moisture excess is 2.8 g/m³ as presented by Ilomets et al. (2018). In normal indoor temperatures (+21.0 °C), relative humidity stays between 24.0-34.4 RH% as presented in Table 2.2.

Table 3. Relative humidity of indoor air in different outdoor conditions and with moisture excess 2,8 g/m³.

Weather zone	Average outdoor temperature in January	Moisture content of outdoor air	Indoor relative humidity in +21,0 °C and with moisture excess +2,8 g/m³
I and II Helsinki-Vantaa	-4.0 °C	3.5 g/m³	34 RH%
III Jyväskylä	-8.0 °C	2.5 g/m³	29 RH%
IV Sodankylä	-13.1 °C	1.6 g/m³	24 RH%

Moreover, if the relative humidity of indoor air increases to, for example, 60%RH, this may mean a much higher moisture excess than 2,8 g/m³ during the heating season. High moisture excess increases the risk of condensation and moisture damage, especially near air leakage or thermal bridges.

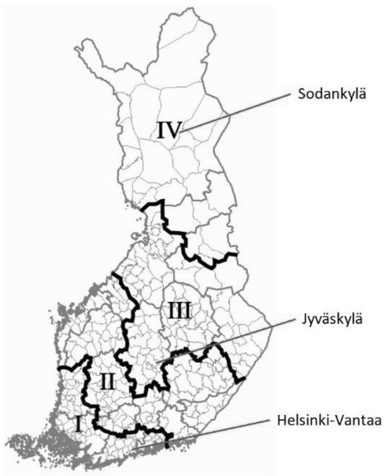


Figure 7. Weather zones in Finland according to the Finnish Building Code (RakMK D3, 2012).

Structures with soil contact

For structures with soil contact, the key moisture source is moisture in the ground. This moisture moves mainly by diffusion and capillary suction from the ground to structures and on to indoor air. The Finnish building stock includes many risk structures in which the following design errors have occurred:

- lack of waterproof membrane or wrong location of membrane (inside load-bearing structure)

- wrong location of thermal insulation (inside load-bearing structure)
- too low water vapour permeability of inner surface materials, or the inner surface material is too sensitive to moisture stress.

The heating of basements and lack of thermal insulation raise soil temperature, which may further increase diffusion from the soil. The use of indoor spaces in basements has increased in many public buildings and this may have triggered problems.

Partition walls and intermediate floors

In partition walls and intermediate floors, typical moisture stress is a consequence of the use of the building or its occupants. Typical reasons for damage are, for example, pipe leaks, building moisture, connections to external walls, lack of waterproofing or other unplanned moisture stress. Capillary movement of moisture may lead to damage to partition walls, especially on ground floors. (Pitkäranta 2016)

2.4 Airtightness of building envelopes

The airtightness of building envelopes is important in many ways. From the perspective of moisture and mould damage, good airtightness is important for the following reasons:

- Air leakage through the building envelope may lead to condensation or increase the moisture content over the critical level inside the structures, which may then lead to moisture and mould damage.
- Leakage through the building envelope may spread impurities to indoor air, if moisture and mould damage are located inside the structure.

Figure 8 presents how airtightness at 50 Pa pressure difference has developed in Finland in recent decades. The data is based on a previous publication (Vinha et al. 2005) and includes 102 detached houses in Finland. The data focuses on the turn of the millennium, but Figure 8 also includes estimated airtightness in older and newer buildings. Estimated airtightness (linear regression) has been added to the original data. This estimate has been calculated from original research data. An average airtightness rate is 3.9 and the standard deviation is 1.8. The best value is 0.5 and the worst 8.9 (Vinha et al. 2005). Variation between buildings is great in absolute values, also as a percentage.

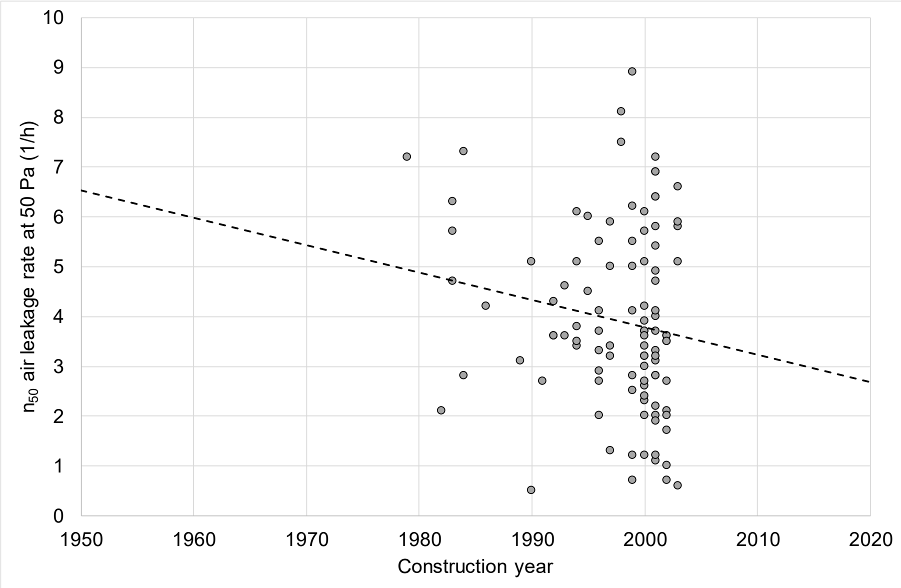


Figure 8. Airtightness rates in Finnish detached houses (Vinha et al. 2005). The data focuses on the turn of millennium, so the dotted line shows an estimate airtightness rates before the 1980s and after the 2000s.

Presented data (Figure 2.2) based on detached houses, not public buildings, as is the topic of this thesis. Unfortunately, similar data are not available from public buildings. Knowledge of the benefits of good airtightness has increased, the general perception in Finland is that air leakages are more common in older buildings and this data from detached houses can be utilised to demonstrate that perception.

Table 4 presents how the old Finnish Building Code (RakMK D5, 2007) divided buildings into different groups according to airtightness. The expectation is that airtightness is better in multi-storey buildings and offices than in detached houses.

Table 4. Typical airtightness in Finnish building stock (RakMK D5, 2007).

Aim of airtightness	Single-family houses	Multi-storied buildings and offices
Good	1-3	0.5-1.5
Average	3-5	1.5-3.0
Poor	5-10	3-7

The data from detached houses (Vinha et al. 2005) point out that average airtightness is probably poor in old buildings built before the 1980s, if classification was done based on old Finnish building regulations. Altogether, this means that in older buildings it is more probable that impurities also spread to indoor air from hidden moisture and mould damage though air leakages.

2.5 Moisture and mould damage

The definition of moisture and mould damage varies between previous scientific studies (e.g. Lawton et al. 1998; Nevalainen et al. 1998; Howden-Chapman et al. 2005; Haas et al. 2007; Salonen et al. 2007; Holme et al. 2008; Haverinen-Shaughnessy et al. 2012). There is thus no exact or generally accepted definition for moisture and mould damage in use in scientific studies. Furthermore, this makes it impossible to compare moisture and mould damage in different countries.

A guideline of World Health Organization (WHO, 2009, p. 2) has defined moisture damage as follows:

*"**Moisture problem or damage; water damage:** any visible, measurable or perceived outcome caused by excess moisture indicating indoor climate problems or problems of durability in building assemblies; moisture damage is a particular problem of building assembly durability; water damage is a moisture problem caused by various leaks of water."*

Furthermore, the definition of excess moisture and mould are as follows (WHO, 2009, p. 2):

*"**Excess moisture:** moisture state variable that is higher than a design criterion, usually represented as moisture content or relative humidity in building material or the air. Design criteria can be simple indicators (e.g. no condensation or relative humidity value) or more complicated representations that take into account continuous fluctuation of moisture (i.e. mould growth index)."*

*"**Mould:** all species of microscopic fungi that grow in the form of multicellular filaments, called hyphae. In contrast, microscopic fungi that grow as single cells are called yeast, a connected network of tubular branching hyphae has multiple, genetically identical nuclei and is considered a single organism, referred to as a colony (Madigan & Martinko, 2005)."*

In Finland mould growth is estimated with material samples cultivated in a laboratory. Estimation of active microbe growth is based on the total amount of growth and also species indicated in moisture and mould damage to building materials. These species are: Acremonium, Actinomycetes, Aspergillus fumigatus, Aspergillus ochraceus, Aspergillus penicillioides/Aspergillus restrictus, Aspergillus sydowii, Aspergillus terreus, Aspergillus ustus, Aspergillus versicolor, Chaetomium, Eurotium, Exophiala, Fusarium, Geomyces, Oidiodendron, Paecilomyces, Phialophora sensu lato, Scopulariopsis, Sporobolomyces, Sphaeropsidales, Stachybotrys, Trichoderma, Tritirachium/Engyodontium, ulocladium and Wallemia (Ministry of Social Affairs and Health, 2015).

2.6 Development of structures in Finland

At the beginning of the 20th century, the most common load-bearing materials were solid masonry walls in multi-storey buildings, and wood in small ones. In wooden buildings, the switch from log and timber frames took place approximately in the 1940s. The development of wooden structures is presented in Figures 9-10 and masonry structures in Figures 11-14.

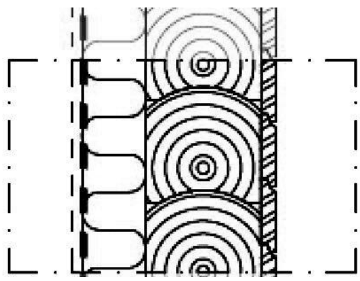


Figure 9. Structural section of external walls in log buildings. The structure consists of interior materials, which sometimes include layer of thermal insulation (approx. 50 mm), a load-bearing log frame (approx. 150 mm) and external surface material, which is usually timber (approx. 20-30 mm). This structure was widely used before the 1940s, but structures have been developed and log houses are still being built today (Weijo et al. 2019).

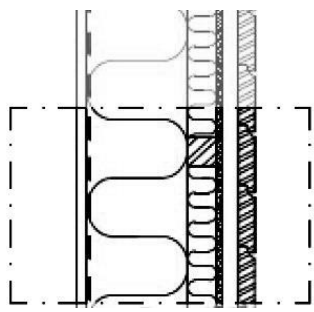


Figure 10. Structural section of timber frame external wall. The structure consists of interior materials (gypsum board or chipboard approx. 10 mm), vapour barrier, frame and thermal insulation (approx. 150-200 mm), wind shield board (approx. 10-20 mm) and external surface material. This structure also corresponds approximately to external walls in modern timber buildings and was from the 1940s, but with small variations (Weijo et al. 2019).

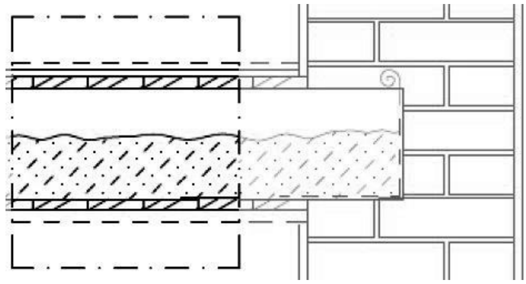


Figure 11. Structural section of wooden intermediate floor in solid masonry building. In older masonry buildings, the load-bearing frame of the intermediate floor was usually wood. The filling material in intermediate floors varies, but typical examples are straw, peat, moss, sawdust, sand or cinder stone. The thickness of filling material is approximately 300-400 mm. This structure is typical of the end of the 19th century and the first decades of 20th (Weijo et al. 2019).

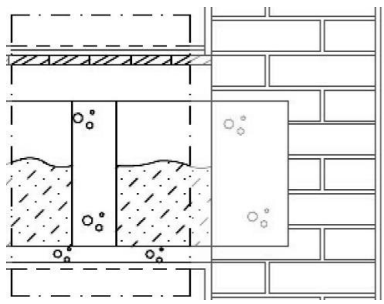


Figure 12. Structural section of a concrete intermediate floor in a solid masonry building. The load-bearing material is in-situ concrete and the filling material varies and may include organic materials. The thickness of filling material is approximately 300-400 mm. This structure became common in the mid-20th century in multi-storey buildings (Weijo et al. 2019).

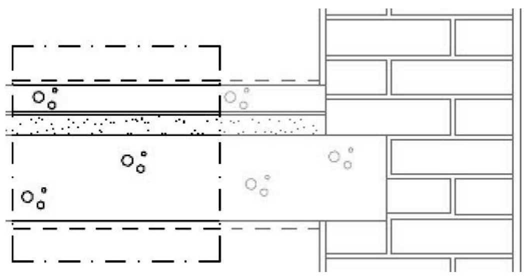


Figure 13. Structural section of a concrete intermediate floor in a solid masonry building. The load-bearing material is a solid in-situ concrete slab (approx. 200 mm). Above this, there may be levelling sand (approx. 30-50 mm) and concrete slab (approx. 50-80 mm). This structure is typical of the 1950s and 1960s. If the external wall is concrete, the intermediate floor may also be a prefabricated solid concrete element (Weijo et al. 2019).

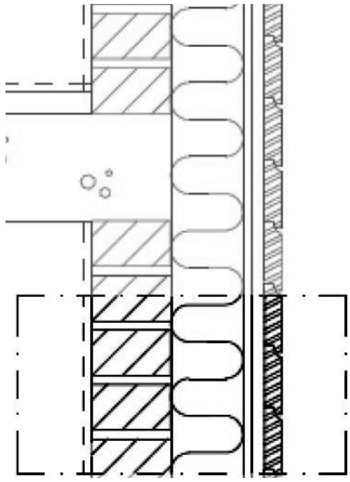


Figure 14. Structural section of a masonry building. The external wall consists of load-bearing masonry (approx. 130 mm), thermal insulation (approx. 100-150 mm) and exterior surface materials. This structure was mainly used in the 1980s (Weijo et al. 2019).

Reinforced concrete structures as a material for the main load-bearing frame started replacing masonry during the 1940s when the focus was on multi-storey- and public buildings. At first, concrete structures were cast-in-situ, and in the late 1950s concrete elements become more popular. Figure 15 presents the structural section of a modern concrete building. In non-residential concrete buildings, the typical load-bearing frame is of the column-beam type, which allows, for example, bigger classrooms in school buildings.

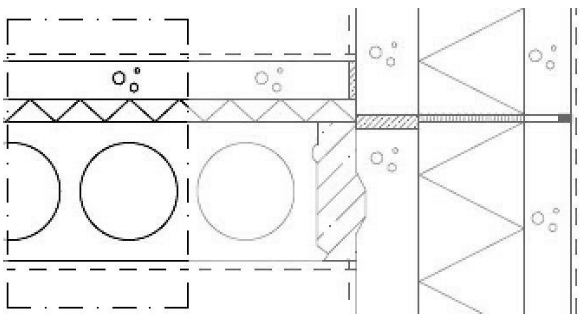


Figure 15. Structural section of modern concrete building. External walls are prefabricated concrete sandwich panels, and intermediate floors are, for example, prefabricated hollow-core slabs (approx. 270-370 mm). A thermal insulation layer (approx. 20-50 mm) on the top of the hollow core slab has been used in the 2000s (Weijo et al. 2019).

All these building materials, log, masonry, wood and concrete, are still used but changes between materials and structure types have not occurred at exactly the same time throughout Finland. Development has also occurred inside these material groups. Good reference sources for Finnish structural types are *Kerrostalo 1880-2000* (Neuvonen, 2006) and the national guideline *Repair of Moisture- and Mould-Damaged Buildings* (Weijo et al. 2019).

2.7 Building material sensitivity to mould growth

The sensitivity of structures or building materials to moisture and mould damage could be estimated with mould growth models. These models help to define the critical conditions and especially moisture level, which lead to moisture and mould damage. Mould growth models can also be utilised once the most probable location of the damage has been defined. In typical Finnish structures, this is usually at the interface between two material layers.

The Finnish mould growth model (Building Physics Research Group, 2020) divides building materials into four mould sensitivity classes (MSC1…MSC4) as presented in Table 5. Classes MSC1 and MSC2 mainly include wood-based and organic products, and classes MSC3 and MSC4 include, for example, concrete, glass and metal. Information about the materials is increasing all the time and the table is continuously being updated.

Table 5. Mould growth sensitivity classes (Annila et al. 2018, Article III) based on original publications (Ojanen et al. 2010 and Viitanen et al. 2010).

Mould growth sensitivity class (MSC)	Materials
MSC1 Very sensitive	Sawn spruce and pine, planed pine, pine sapwood
MSC2 Sensitive	Planed spruce, glued wooden boards, PUR with paper surface, gypsum boards, paper-based products
MSC3 Medium-resistant	Carbonated concrete, aerated and cellular concrete, glass wool, polyester wool, cement-based products
MSC4 Resistant	PUR with polished surface, glass, metals, alkali, new concrete

Figure 16 presents the main data from the Finnish mould growth model (Building Physics Research Group, 2020). At typical Finnish indoor air temperatures (about +21 °C), mould growth starts in sensitivity classes MSC1 and MSC2 when relative humidity is over 80%. In sensitivity classes MSC3 and MSC4, mould growth starts when relative humidity is over 85%. However, mould growth is highly dependent on the length of time during which relative humidity exceeds these limits and also on how much these limits are exceeded.

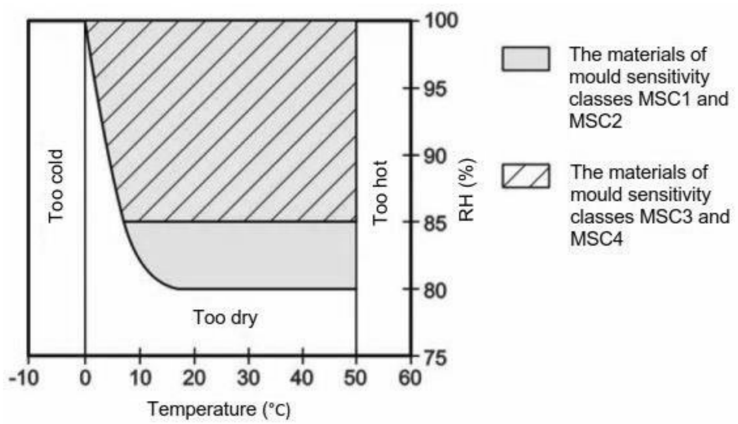


Figure 16. Finnish mould growth model: favourable relative humidity and temperature conditions for mould growth in different mould sensitivity classes (Building Physics Research Group, 2020).

In Finland, the location of moisture and mould damage, which diminish indoor air quality, must be such that impurities can spread into indoor air. This especially concerns damage hidden and located inside the structures so, in moisture performance assessments and other condition inspections, it should be pointed out how the impurities may spread from the damaged area to indoor air through the air leakages, so that exposure can be assessed.

When typical Finnish structures (see Chapter 2.6 *Development of structures in Finland* and Figures 9-15) are under consideration, it can be seen that basically all structures contain materials, which belong to mould sensitivity classes MSC1 and MSC2. The main material or materials of structures may belong to sensitivity classes MSC3 and MSC4, but this does not prevent moisture and mould damage, if more sensitive material is located under critical conditions.

It is basically certain that some air leakage routes from structures to indoor air occur in every building in the Finnish building stock. Altogether, the sensitivity of materials to mould growth and the lack of airtightness mean that the critical moisture level for moisture and mould damage in Finland is considered to be relative humidity of 80% in this study.

2.8 Moisture performance assessment

Moisture performance assessment or building moisture and indoor air quality assessment is condition investigation whose main goal is to determine all moisture and mould damage and also other indoor air impurities. National updated guidelines for assessments were published in 2016 in Finland (Pitkäranta, 2016). The previous one was published in 1997 (Ministry of the Environment, 1997). The new guidelines have gathered practical experience from the field, so similar research methods and protocols were already used before these new guidelines.

Moisture performance assessments consist of four main phases, which are: a) gathering of background information, b) field studies, c) laboratory tests, and d) analyses and conclusions. These steps and their main content are presented in Figure 17 (Annila et al. 2016). The assessments are not always uncomplicated as presented in Figure 17, so the same phases may be repeated after the first results and findings, and they may also be performed simultaneously.

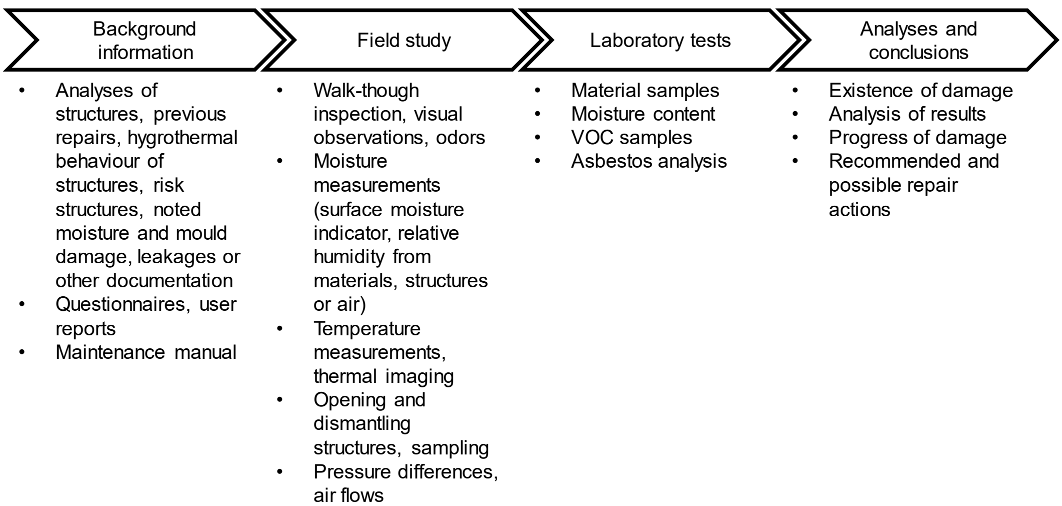


Figure 17. The four main phases of moisture performance assessment and their main content (Annila et al. 2016).

The main products of the assessments are reports, which describe the condition of every structure, point out all the examined indoor air impurities and give recommendations on how to repair all damage and how to ensure healthy indoor air conditions (Pitkäranta, 2016). These reports are the most important sources of information for the refurbishment of damaged buildings (Weijo et al. 2019).

3 RESEARCH MATERIAL AND METHODS

3.1 Reports of moisture performance assessment

The research material consists of the reports from moisture performance assessments. Originally, these assessments were independent condition investigations for building owners. The assessments were not performed in the same way as a scientific study, but research methods between assessments are similar and follow the national guidelines (Pitkäranta, 2016), even though they were performed before the publication of the updated national guidelines.

Public buildings are often built in many stages in Finland. At the start, the same moisture performance assessment may have included all these phases but, during the research, the data were divided up and all phases examined separately. For example, one public building consists of phases carried out in the 1930s, 1958 and 1960, and the last phases consist of two separate buildings. All these phases were handled in the same moisture performance assessment report but, in the research material, they are four separate buildings.

Many companies and professionals performed the original assessments, so it is now impossible to confirm all observations, results and conclusions. In the processing of the research data, the buildings were divided into two categories:

a) buildings where moisture performance assessments are thorough and correspond to national guidelines
   - this group includes 168 buildings
b) building that were examined partially, but the condition inspection followed the national guidelines
   - this group includes 123 buildings

Thorough moisture performance assessment basically means that all structures were examined in the original study by many different research methods. The division was made from the perspective of moisture and mould damage to structures. From other perspectives, for example, of ventilation or how other indoor air impurities were examined, the research data may be divided differently. However, group b) also included professionally produced reports, but original research concentrated only on some structures, for example, the external walls and roof.

Unreliable reports from moisture performance assessments were totally excluded from the research. The number of these is unknown because their data have been deleted.

Examined buildings were located all over Finland, but data focused on large Finnish cities like Helsinki, Tampere, Turku and their regions, as presented in Figure 18. The division was calculated according to the number of buildings. The data includes a total of 291 buildings. The share of these that are in the cities corresponds well to the Finnish building stock and the locations of inhabitants, so focus was targeted at the areas where the number of buildings and inhabitants are high.

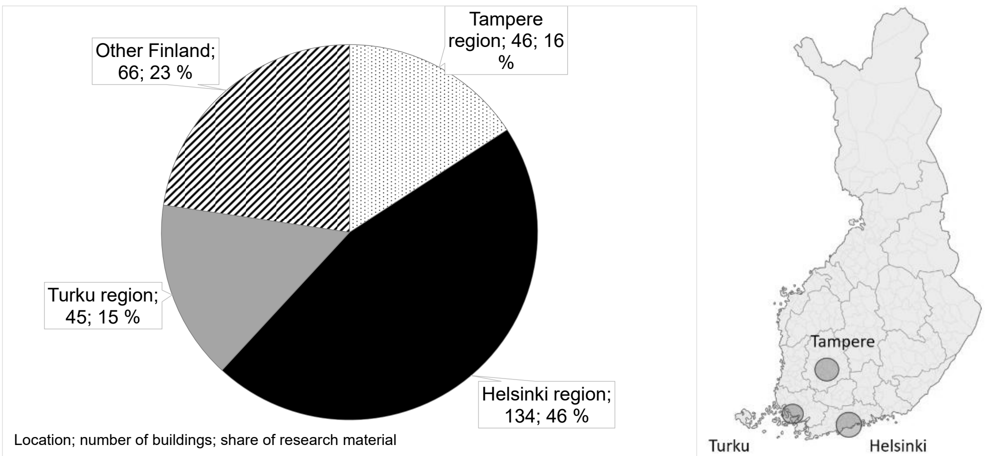


Figure 18. The division of examined buildings between different regions and the locations of these regions. Most of the examined building were located in the Helsinki, Tampere and Turku regions. The total number of buildings in the research material is 291.

Assessments and research material were gathered during the following studies:

- Annila's doctoral thesis (2013-2021)
- COMBI – Comprehensive development of nearly zero-energy municipal service buildings (2015-2018)
- HKPro3 – Assessment of state-supported mould remediation projects, follow-up research (2014-2015).

3.2 Moisture and mould damage database

A moisture and mould damage database was formed from reports of moisture performance assessments. The study focuses only for moisture and mould damage to different structures and methods of detecting damage, so the database contains only data about these. The database includes data from 291 public buildings such as schools (58.8%), kindergartens (24.7%), office and other buildings (7.2%) and health care facilities (9.3%).

The database includes the basic features of buildings such as construction year, building type, number of floors, main building materials and location. Basic data from the original assessments have also been gathered. This includes company names and dates of assessments, but the material has been examined anonymously.

Figure 19 presents years when the original moisture performance assessments were performed. The figure includes all 291 buildings from the database. Table 6 shows when thoroughly examined buildings were examined (N = 168 buildings).

The buildings have been divided into six age groups according to construction year. These age groups are based on *Kuntien rakennuskanta 2005 (Municipal building stock)* (Vainio et al. 2006) and databases of Official Statistics of Finland (OSF, 2019). The groups are:

- buildings built before 1950
- buildings from the 1950s
- buildings from the 1960s
- buildings from the 1970s
- buildings from the 1980s
- buildings built after the 1990s.

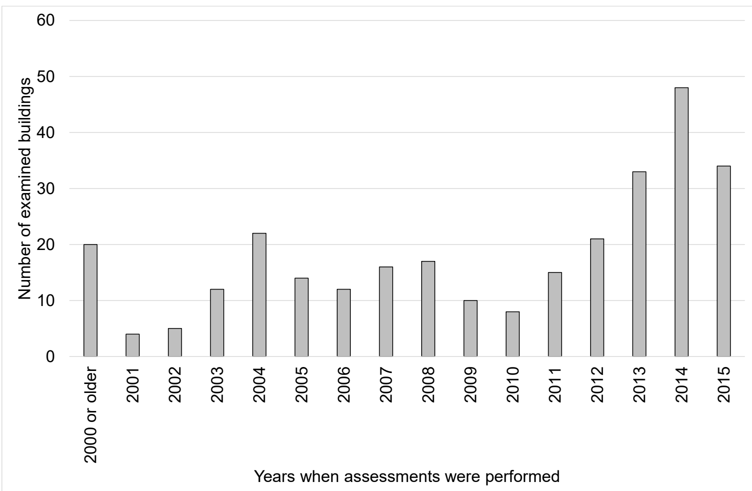


Figure 19. Years when original moisture performance assessments were performed (N = 291 buildings).

Table 6. The number of buildings in different age groups, average construction years and standard deviation of age (N = 168 buildings).

	Before 1950	1950-1959	1960-1969	1970-1979	1980-1989	After 1990
Number of buildings	27	33	29	36	35	8
Group average construction year	1915	1954	1964	1974	1986	1995
Standard deviation of age	23.7	3.0	3.0	2.9	3.1	2.7

The age of the building is an important factor affecting damage as previous studies have been pointed out (see Chapter 2.2 and Table 2), so Figure 20 presents the age of buildings when their moisture performance assessment was performed. Most of the buildings (43.3%) were examined at the age of 20-40 years. The percentages for other ages were as follows: under 10 years 4.1%, 10-20 years 7.6%, 40-60 years 25.1% and over 60 years 19.9%. Especially in older buildings (age over 40 years), it is possible that the assessments performed were not the first. It should be noted that 12 buildings (4.1%) were under 10 years old when their moisture performance assessment was performed.

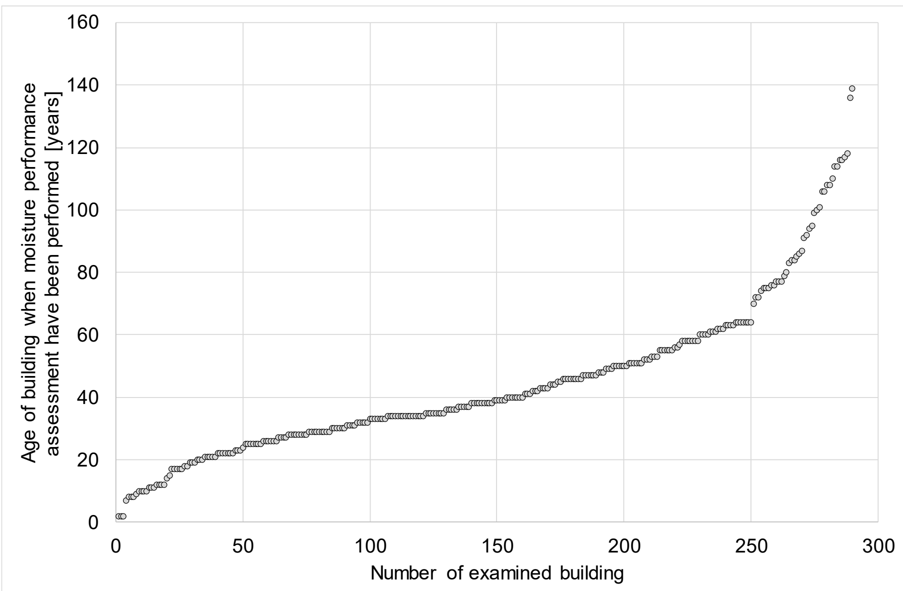


Figure 20. Age of buildings when moisture performance assessment was performed (N = 291 buildings).

The data on moisture and mould damage comprise examined structures, condition investigation methods, result of material samples and moisture measurements, and visual observations of the condition investigator. Table 7 presents a simplified example from the database. Table 7 has been refined from Article I (Annila et al. 2016).

Table 7. Four simplified examples from the moisture and mould damage database: the data present how damage to different structures have been examined from original moisture performance assessments.

Structure	Visual observation	Active leakage	Surface moisture detector	Relative humidity	Mould growth	Undamaged or damaged
Partition wall	Discolouration		Dry			0
Wall in soil contact	Paint peeling off		Moist	86.3 %RH		1
Slab-on-ground	Discolouration		Extremel y moist		Yes	1
Intermediate floor	Visible moisture damage	Yes				1

A total of 168 public buildings' moisture performance assessments were thorough when compared to the methodology presented in the national guidelines (Pitkäranta, 2016). In these buildings, the original reasons for condition investigations were as follows:

- indoor air quality problems and the determination of the need for repair 45.2%
- indoor air quality problems 25.0%
- determination of the need for repair 20.2%
- reasons for assessment were not mentioned in 9.5% of the reports but it is probable that the previous reasons were activators for the assessment (Annila et al. 2018, Article III).

The research material consists of buildings for different purposes. The data includes schools, kindergartens, health care facilities, offices and some other public buildings. Table 8 presents the proportion and purpose of the buildings. Schools and other educational buildings form the largest part (58.5%) of the research material.

Table 8. The purpose of the buildings and their proportion in the research material (N = 291 buildings).

Purpose of building	Number of buildings	Share of examined buildings
Schools and other educational buildings	171	58.8%
Kindergartens	72	24.7%
Health care facilities	27	9.3%
Other buildings	21	7.2%

Not all the moisture and mould damage database and all the reports from the moisture performance assessments were used in research material in all the studies (Article I-IV), so the research material used is defined more precisely in every article.

3.3 Definition of moisture and mould damage

In this thesis, structures were considered to be moisture- and mould-damaged if at least one of the following criteria was met:

I. Mould damage, visible to the naked eye without magnification.

II. Unrepaired, active water leakage detrimental to the structure or building material affected.

III. A structure or building material found to be moist, extremely moist or wet by a surface moisture detector based on a five-step assessment scale: dry, a little moist, moist, extremely moist and wet.

IV. Relative humidity of the structure exceeds 80% in a drill-hole measurement.

V. A material sample shows active microbial (fungal or bacterial) growth. The fungal and bacterial colonies are determined by dilution plating MEA (2% malt extract agar) agar, DG18 (dischloran 18% glycerol agar) or TYG (tryptone glucose yeast) agar.

The same definition has been used in Articles II, III and IV (Annila et al. 2017, 2018 and 2020 respectively). The definition based on the literature review (see Chapter 2 and literature reviews of Articles I-IV) and basic properties of common Finnish structures and the building materials used in them.

Criteria I and II are the most obvious: if the condition investigator sees that the structure is mould-damaged, no further or more precise analysis is needed to determine whether that structure is moisture and mould-damaged. The same applies to active water leakages. Of course, more precise research methods like moisture measurements and the dismantling of structures are useful to determining the reason for the damage and gathering enough initial data for refurbishment.

Criterion IV and the limit value for relative humidity of building material are based on analysis of mould growth models, especially the Finnish mould growth model (Building Physics Research Group, 2020) and typical structures in Finnish public buildings. Almost all these structures contain materials belonging material classes MSC1 and MSC2, which are most sensitive to mould growth according to the Finnish mould growth model. In these two sensitivity classes, mould growth starts at a relative humidity of 80% at typical indoor temperatures (around +20 °C).

Criterion III is based on the same knowledge of the Finnish mould growth model and typical Finnish structure types as criterion IV. Condition investigators typically classified structures by the results of the measurements of a surface moisture detector. This classification points out structures or parts of structures where moisture content is considered to be exceptionally high, which further indicates moisture or mould damage. Surface moisture measurements are usually used to define the extent of the damage and they are usually confirmed by more precise methods, for example relative humidity measurement with drill-hole measurements or material samples.

Criterion V is based on *Decree of the Ministry of Social Affairs and Health on Health-related Conditions of Housing and Other Residential Buildings and Qualification Requirements for Third-party Experts* (Ministry of Social Affairs and Health, 2015). This decree and its operating guidelines (Valvira, 2016) define how to analyse microbe growth in building materials and what kind of growth is considered as mould damage.

3.4 Classification of structures

Structures have been divided into seven main categories and further into 14 subcategories as presented in Table 9. In Finnish public buildings, it is common for façade material to vary as presented in Figures 21. Afterwards, it is basically impossible to connect moisture and mould damage with certain façade material, so the classification is based on the vertical load-bearing material of the building. In Articles I (Annila et al. 2016) and II (Annila et al. 2017) slab-on-ground and ground floor with crawl space are considered in the same category ‘base floor’.

Table 9. Classification of structures (Annila et al. 2018).

	Main category	Subcategory
1	Roof	Ridge roof
		Flat roof
2	Slab-on-ground	Slab-on-ground
3	Ground floor with crawl space	Wooden ground floor with crawl space
	(attic floor structures)	Concrete ground floor with crawl space
4	External walls	External wall in concrete building
		External wall in timber frame building
		External wall in log building
		External wall in masonry building
		External wall in mixed frame building
5	Wall in soil contact	Wall in soil contact
6	Intermediate floor	Concrete intermediate floor
		Wooden intermediate floor
7	Partition wall	Partition wall

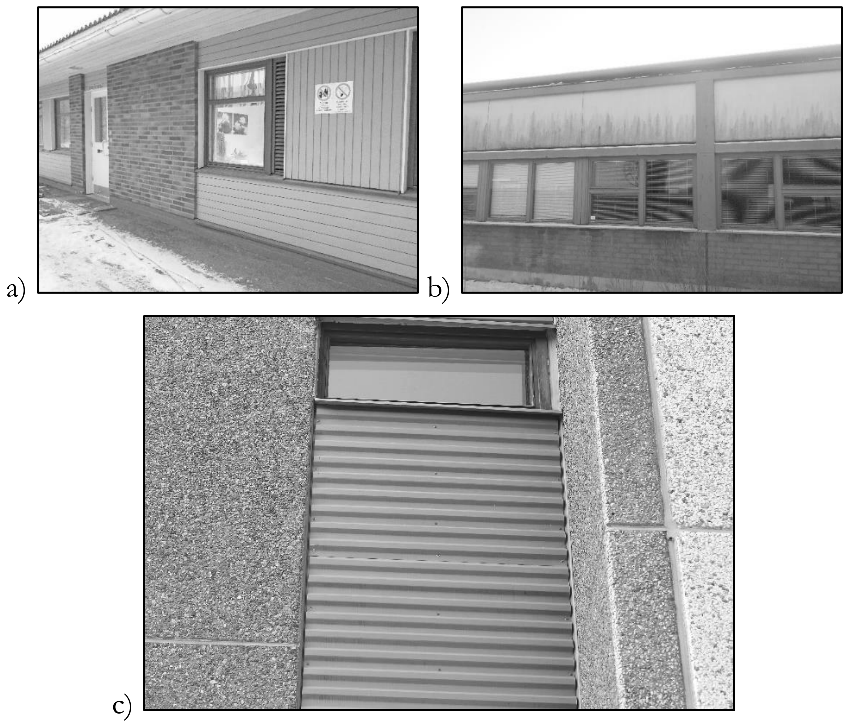


Figure 21. It is very common for façade material to vary in Finnish public buildings, especially around the windows. These examples include changes between a) masonry and wooden panels, b) masonry and a ventilated façade based on cement boards, and c) concrete and a ventilated façade based on metal panels.

4 MAIN RESULTS AND DISCUSSION

4.1 Practical experiences from moisture performance assessments

Previous studies (e.g. Asikainen, 2008 and Haverinen-Shaughnessy et al. 2008) have already pointed out that renovating buildings is typically a long process counted from detecting problems to solving them. Asikainen (2008) estimated that repairs typically take 2-5 years after the occurrence of health symptoms. After that, it takes about 6-12 months before indoor air conditions are stabilised to a normal level (Haverinen-Shaughnessy et al. 2008). This is also a widely held view among Finnish occupants of the buildings.

The set study question and results of Article I (Annila et al. 2016) point out that moisture performance assessments and the detection of all moisture and mould damage are also a long process. The period between the research plan and reporting the results is over six months in 42.9% of cases (Annila et al. 2016). The length of different time periods and comparison between them is presented in Figure 22.

A dilution time of material samples is two weeks, so it takes typically 3-4 weeks before all results have been gathered and analysed after the first field study days. It is also common for the first results to cause an extension of field studies, which doubles the time required for the moisture performance assessment. Final conclusions and planning to recommended repair actions also takes time, and of course the urgency of professionals also has an effect. After all, 2-3 months may be the realistic waiting time from field study to the final report of a thorough moisture performance assessment in a public building but, as Figure 22 points out, this has not been realised in practice in previous years.

When other factors such as the time of the procurement process and scheduling of field studies during the normal use of the building are included, the length of the process may be much longer than the actual moisture performance assessment. In conclusion, the times of exposure to indoor air impurities are long if measured from the time when moisture and mould damage has formed until refurbishment has finished.

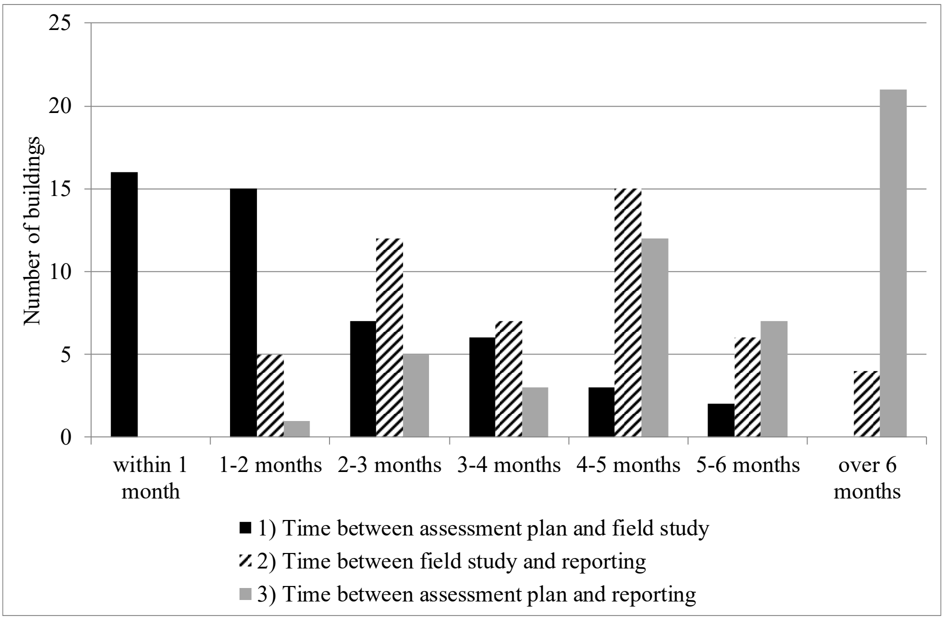


Figure 22. Lengths of different phases of moisture performance assessments (Annila et al. 2016)

In the last few years, moisture performance and indoor air quality assessments improved in Finland. A step in right direction were the updated national guidelines for assessments (Pitkäranta 2016). However, the guidelines have basically been updated to the level already used by professionals in the assessments, so it did not offer much new information. The main aim is to ensure that every condition investigator uses the same methods and principles in the assessments. The guidelines also help to determine what thorough assessment should include, which also makes the performing of assessments more efficient.

The other significant finding from the research material was that visual observations and surface moisture measurements are widely used field research methods in thorough assessments. The visual observations and surface moisture measurements were part of the detection of moisture and mould damage in 73.8% of cases (Article I: Annila et al. 2016).

The research material of Article I (Annila et al. 2016) includes a total of 920 cases of moisture and mould damage, which were detected by 1,025 measurements, observations or samples, so one case of damage may be detected by several different methods. Figure 23 shows which criteria determine that a structure is moisture- and mould-damaged, and the share of detections confirmed by other methods. The shares of confirmed measurements were 47%, 14%, 12%, 35% and 30% respectively for criteria I-V.

It is possible that, if the more precise criteria IV and V were used in moisture performance assessments to detect moisture and mould damage, the visual observations (criteria I and II) or the results of the measurements by the surface moisture detector (criteria III) may not have been written in the reports. It is also possible that the reports did not point out clearly that measurements, sampling or observations are done from the exact same locations, or that confirmation may have been done in the same room but not the exact same location. In conclusion, the share of confirmed measurements may be higher than presented.

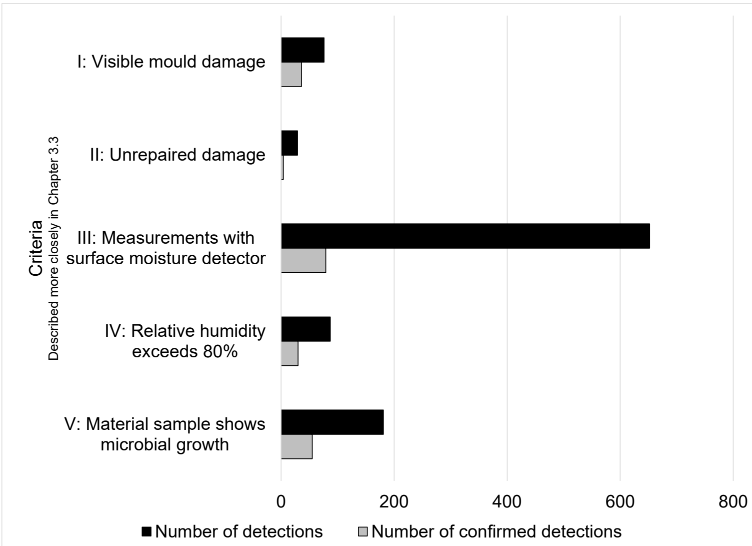


Figure 23. Criteria used to detect moisture and mould damage to structures and share of confirmed detections.

Moisture performance assessment reports did not reveal which measurements or observations were carried out first in the field study. It is probable that criteria I, II and III are first-hand methods and these observations were confirmed by more precise methods (criteria IV and V). However, the results show that the detection of moisture and mould damage in thorough moisture performance assessments is not based only on material samples or drill-hole measurements, so the role of visual observations and surface moisture measurements is significant.

Figure 24 shows which methods are used to determine whether structures are moisture- or mould-damaged (Annila et al. 2016). The role of measurements with a surface moisture detector (criterion III) is considerable in every structure except roofs: 48.4%-77.1% of damage was detected with a surface moisture detector, whilst in roofs it was only 13.3%. The role of material samples (criterion V) is significant in roof and external walls, with shares of 48.9% and 39.6%, respectively. The share of visual inspection (criteria I and II) varies between 5.3% and 8.8%, irrespective of structure.

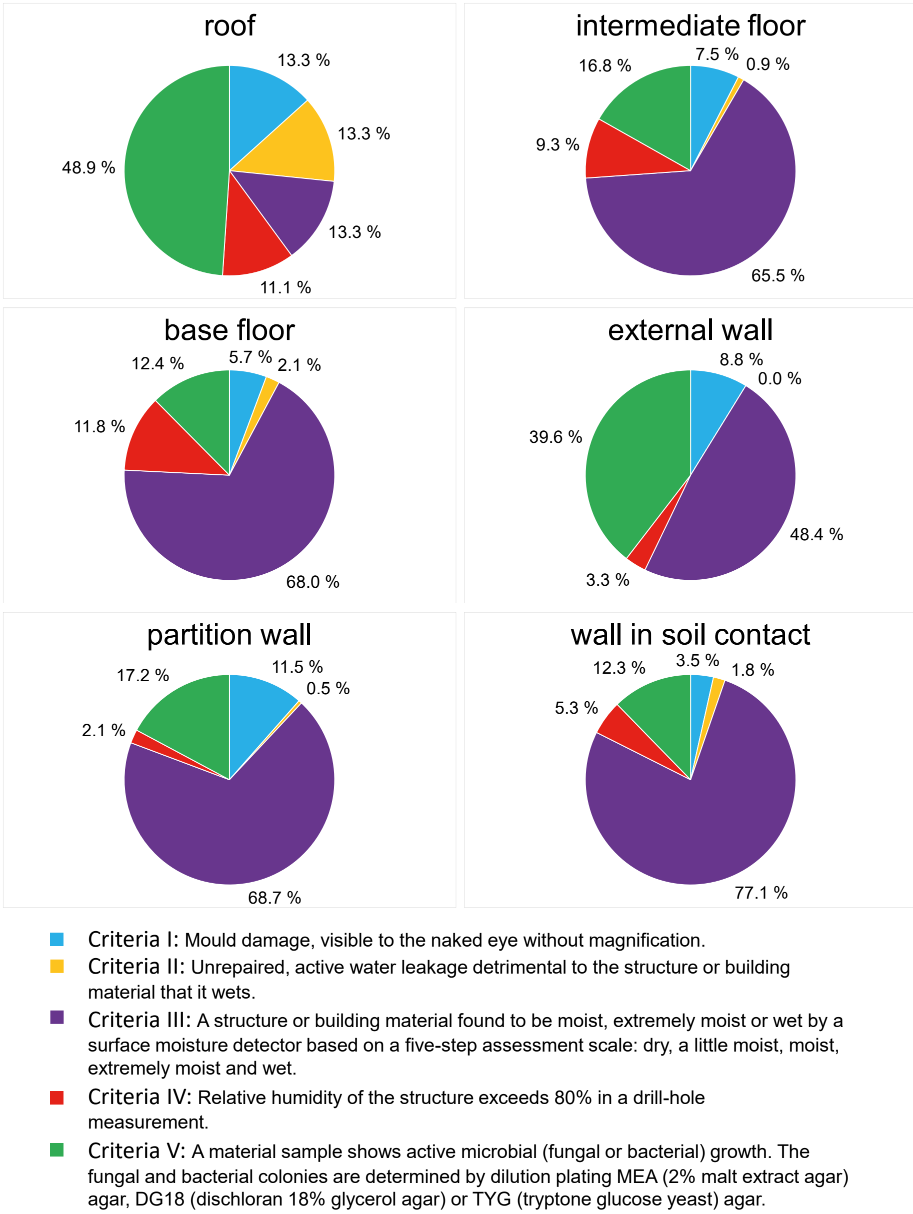


Figure 24. Methods used to detect moisture and mould damage in different structures (Annila et al. 2016; Article I)

The detection methods used reflects the properties of Finnish structures. For example, in slab-on-ground and walls in soil contact, it is usually possible to measure a critical or indicative material layer with a surface moisture detector. In this case, the critical or indicative material layer is the one where moisture content is high, and which indicates the condition of the structure.

The most critical material layer of roofs, external walls and ground floors with crawl space is usually thermal insulation, so the material samples and dismantling of structures may be the best way to detect moisture and mould damage in these structures.

4.2 Moisture and mould damage to public buildings

4.2.1 Extent of moisture and mould damage in structures

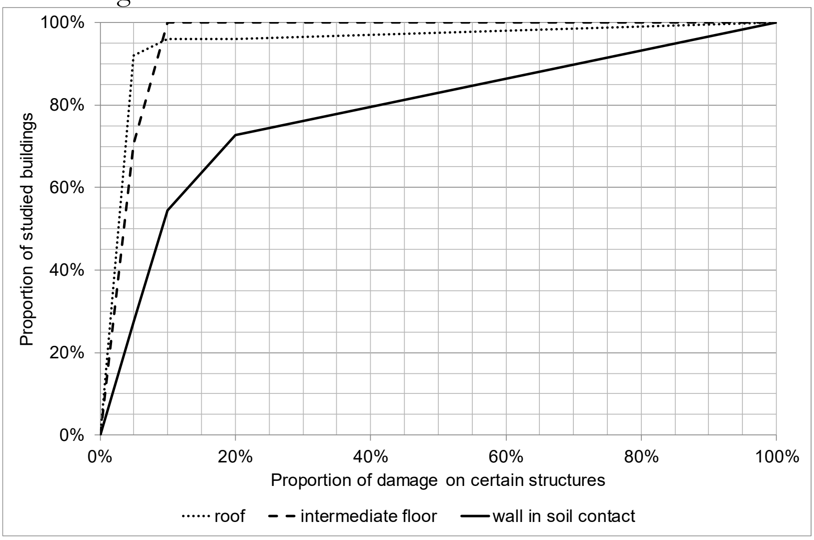
The extent of moisture and mould damage in different structures was the main research question in Article II (Annila et al. 2017). The study was a case study of 25 buildings. The study indicates that, on average, moisture and mould damage are more point-sized than widespread. The most widespread damage was in structures in soil contact, i.e. walls in soil contact and the base floor. The percentages of damage in these two types of structure were 16.3% and 12.5% of the whole structure, respectively. The lowest damage rates were found in partition walls (2.4%), external walls (2.6%) and intermediate floors (2.5%) as presented in Table 4.1 (Article II: Annila et al. 2017). The share of damaged structures was calculated from floor plans using data on how condition inspectors reported the extent of the damage.

Table 10 also presents the mean and maximum values of the damaged area, and standard deviation. It is important to notice that the areas of detected damage and need for repair are not equal. The structure may be only partly damaged but, in practice, it may be better to repair it more widely.

Table 10. Proportion of damage to moisture- and mould-damaged structures (Annila et al. 2017).

	Wall in soil contact	Base floor	Roof	External wall	Intermediate floor	Partition wall
Mean value	16%	13%	5%	3%	3%	2%
Maximum value	75%	82%	100%	27%	9%	22%
Standard deviation	22%	19%	20%	6%	3%	5%

Figure 25 shows the average proportion of damaged structures. The original data (Annila et al. 2017) has been divided into two figures for more precise examination. Figure shows 5-, 10- and 20% fractals. The extent of damage to base floors and walls in soil contact in 80% of buildings was on average below 40% and 20%, respectively. In other structures, the extent of damage was on average below 10% in 80% of buildings. Thus, the share of buildings with widespread damage is low. The data includes 25 buildings.



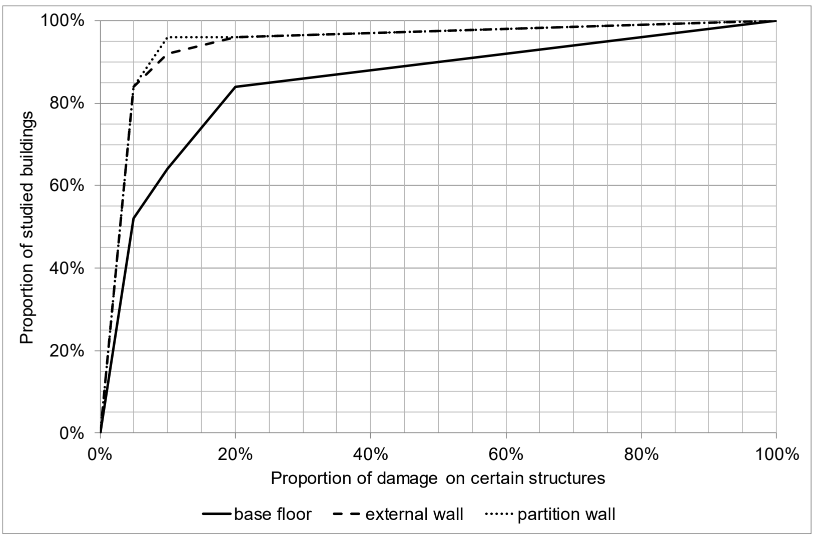


Figure 25. Distribution of damage to different structures. The data is counted from 25 buildings, which were the research material in article II (Annila et al. 2017).

The findings highlight the need for thorough moisture performance assessments. When damage is more point-sized than widespread, this makes it difficult for assessments to detect all damage. The number of measurements and observations should be sufficiently high that it guarantees that all repair needs will be detected before refurbishment. In practice, it may be easier to point out that a structure is moisture- and mould-damaged than undamaged.

The standard deviation is significant when compared to mean values. This means a huge variation between buildings and also that every building should be examined individually and the number of measurements, samplings and dismantling of structures should be high enough.

The results also indicate that buildings are multi-problematic, meaning that moisture and mould damage are detected in many structures (Annila et al. 2017) when a moisture performance assessment has been performed.

4.2.2 Need to repair moisture and mould damage in different structures

Number of damaged structures

The need to repair structures was the main research question in Article III. The existence of repair need was determined by similar criteria to moisture and mould damage to structures as presented in Chapter *3.3 Definition of moisture and mould damage* (Annila et al. 2018; Article III).

Public buildings are multi-problematic in terms of moisture and mould damage. On average, 3.1 structures were found to be damaged when a thorough moisture performance assessment was performed (Annila et al. 2018; Article III). The trend is almost linear: the older the building, the more moisture- and mould-damaged structures there were, as shown in Figure 26.

Buildings built before 1950 make a difference to the linear trend. A major reason for this is that the age group 'before 1950' probably includes buildings in their best condition, whilst the most damaged buildings are not in use anymore or have been renovated at least once during their service life. The average size of old public buildings is also smaller and they are simpler, which means that the total number of structures is lower, as presented in Figure 26. The maximum number of damaged structures is seven according to the number of main category structures (see Chapter *3.4 Classification of structures*).

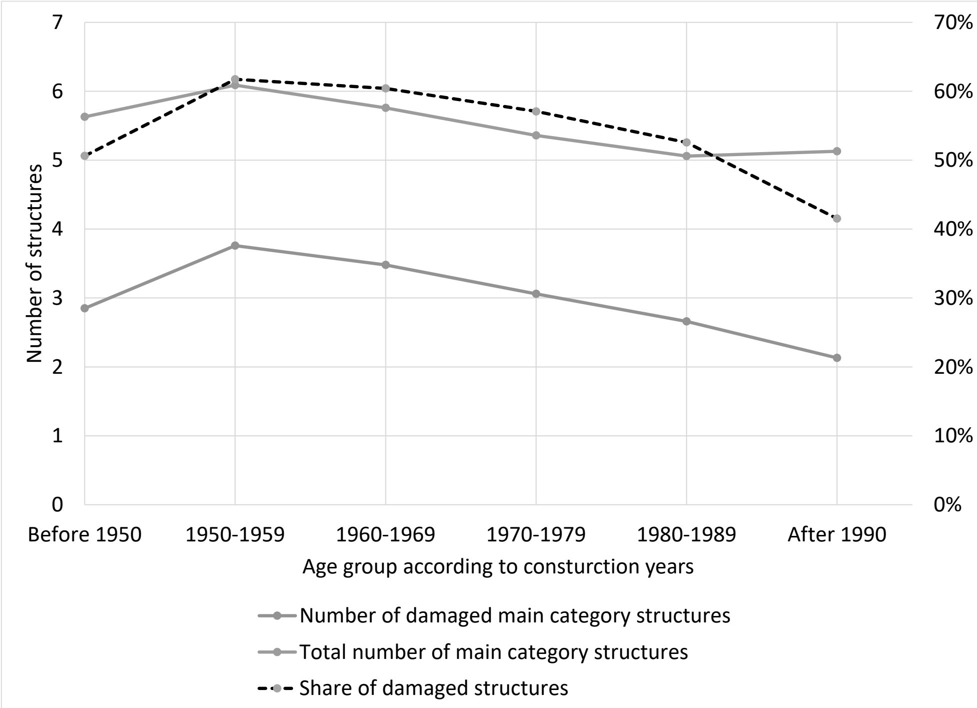


Figure 26. Number of moisture- and mould-damaged structures.

Estimation of number of damaged structures

The time needed for moisture and mould damage to occur can be estimated by linear regression if the age group that is probably the most heterogenous 'before 1950' is ignored. According to this linear regression, it takes 25.6 years for a new structure to form moisture and mould damage. This examination resulted in Equation 1, which can be used to estimate the number of cases of moisture and mould damage. The research data has been gathered from the moisture and mould damage database, so the results are not generalisable to the entire building stock. Reference buildings should also be included in the research data before this generalisation can be done.

N_{mmd} means the number of moisture and mould damaged structures, and y is the age of the building. The difference between buildings is significant, so $E_{80\%}$ is an error term (Eq. 2) representing the range that includes 80% of buildings, based on the research material. However, the research material only consists of damaged buildings, so this formula is not suitable for the entire buildings stock, and also requires more study before it can be widely adopted (Annila et al. 2018).

$$N_{mmd} = 1.5 + \frac{y}{25.6} \pm E_{80\%} \quad (1)$$

$$E_{80\%} = \frac{y}{57.0} + 0.9 \quad (2)$$

The error term $E_{80\%}$ (Eq. 2) and variation between buildings increase when the age of the building increases. Moisture and mould damage to structures is a consequence of many different factors. During the aging of a building, the variation in these external stress factors increases, which also explains variations in degree of damage to older buildings.

Equations 1 and 2, however, raise some interesting findings. The formula indicates, for example, that even in new buildings (less than 1 year old), there exist on average 1.5 moisture- and mould-damaged structures. A range of variation is 0.6-2.4 moisture- and mould-damaged structures per public building.

Figure 27 presents estimates of the number of moisture- and mould-damaged structures based on construction year. The calculation was made in 2019. It is noted that, during the construction phase, there are sometimes problems with moisture, especially with weather protection, building moisture or the drying of concrete, so the estimate may be near the truth.

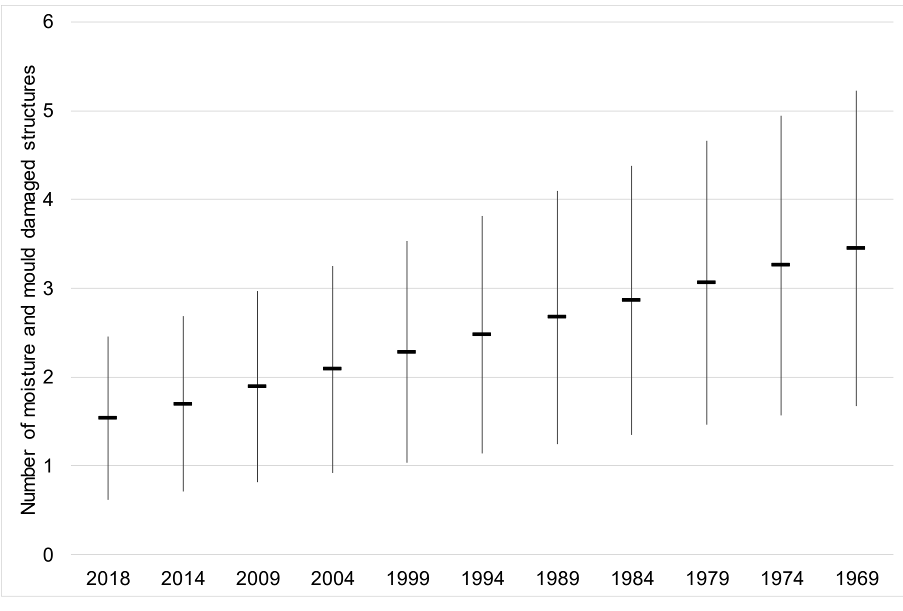


Figure 27. Estimates of moisture- and mould-damaged structures based on construction year, calculated in 2019.

There are many factors that affect moisture and mould damage, and also the time that passes before damage occurs. These and other factors should be studied more precisely before these equations are widely adopted to give an estimate of the speed of moisture and mould damage.

Damage to different structures

The need for the repair of moisture and mould damage was highest in timber-framed ground floors (85%), slab-on-ground structures (82%), external walls in concrete buildings (67%) and walls in soil contact (56%) as presented in Tables 11 and 12 (Annila et al. 2018; Article III). Numerous cases of damage to structures with soil contact reflect the lack of understanding about moisture stress from soil during the 20th century in Finland.

External walls were classified according to the load-bearing frame of building, because afterwards it is impossible to determine the façade material from reports. A typical example in Finnish public buildings is changes in façade materials, for example around the windows as shown in Figure 21. External walls may be analysed for moisture and mould damage, but façade material is not mentioned in the moisture performance assessment reports.

The lowest need of repair of moisture and mould damage was in roofs (29-30%) and external walls in masonry buildings (on average 37%) (Annila et al. 2018; Article III). As can be noted in Tables 11 and 12, the repair need in many structures is over 50%, meaning that damage is more probable than non-damage. Also, at this point it should be noted that the research material consisted only of damaged buildings and these values do not represent the situation of the entire Finnish building stock. Tables 11 and 12 include only those categories where the number of buildings is equal or greater than five. For example, the total number of log buildings after 1950 is below five in every age group. Thus, empty cells do not mean that there is no repair need.

Table 11. Need to repair moisture and mould damage in different structure.

	Roofs		External walls				
	Ridge roof	Flat roof	Wall in soil contact	Concrete building	Masonry building	Timber framing building	Log building
Before 1950	41%		61%		31%		50%
1950-1959	39%		63%	86%	60%		
1960-1969	19%	31%	55%	62%		50%	
1970-1979	23%	48%	56%	83%		44%	
1980-1989	37%	13%	47%	85%	20%	69%	
after 1989	14%			20%			
average	29%	30%	56%	67%	37%	54%	50%

*empty cells: The research material from some structures is considered too minor, which is the reason for empty cells. These structures may also be damaged if they exist.

Table 12. Need to repair moisture and mould damage in different structures.

	Intermediate floors		Partition walls	Slab-on-ground	Ground floor with crawl space	
	Concrete	Timber			Concrete	Timber
Before 1950	57%	43%	30%	77%		85%
1950-1959	57%		64%	84%	40%	
1960-1969	57%		72%	96%	56%	
1970-1979	60%		50%	74%	33%	
1980-1989	43%		37%	84%	50%	
after 1989	20%		63%	75%		
average	49%	43%	53%	82%	45%	85%

*empty cells: The research material from some structures is considered too minor, which is the reason for empty cells. These structures may also be damaged if they exist.

It should be noted that the research material is not a random sample of the building stock in Finland, so these damage rates do not reveal the condition of all public buildings.

Construction techniques and used structures changed considerably during the 20th century in Finland (see Chapter *2.6 Development of structures in Finland*). Because of this, some structures occur only in certain age groups, for example timber ground floors, so it is impossible to determine any differences between types of damage to structure in different decades.

4.3 Reliability of visual inspection and moisture mapping of moisture and mould damage

In thorough moisture performance assessments, moisture and mould damage to structures is detected by many methods (Article I). This set research question estimates cases where moisture and mould damage has been detected by light research methods like visual observations and measurements with a surface moisture detector.

The study reveals that 70% of moisture and mould damage could be detected by visual inspection and moisture mapping without dismantling structures (Annila & Lahdensivu, 2020). The remaining 30% of damage is thus hidden. Its detection is very similar as a previous study (Pirinen 2006) pointed out. In Pirinen's study, 1/3 (29%) of cases of moisture and mould damage were hidden, but the research material and research question are different, even though moisture and mould damage and the Finnish building stock were examined.

The reliability of visual inspection in the detection of moisture and mould damage varies between structures and construction period as presented in Tables 13 and 14. These tables present only those categories containing five or more buildings. The table indicates the share of cases where moisture and mould damage were detected by visual inspection with surface moisture measurements. The reliability of detecting moisture and mould damage without dismantling structures is highest in slab-on-ground structures (88%), external walls in log buildings (86%) and concrete intermediate floors (84%). The lowest values were in external walls of concrete buildings (50%), flat roofs (56%) and external walls of timber-framed buildings (57%) (Annila & Lahdensivu 2020). The results show that moisture and mould damage can be detected most easily in the simplest structures, whilst hidden damage is most often in structures consisting of many layers of different materials.

Table 13. Reliability of visual inspection in detecting moisture and mould damage to different structures (Annila & Lahdensivu, 2020)

	Roofs		External walls				
	Ridge roof	Flat roof	Wall in soil contact	Concrete building	Masonry building	Timber framing building	Log building
Before 1950	91%		82%		50%		83%
1950-1959	62%		80%	67%	83%		
1960-1969	33%	50%	83%	46%		33%	
1970-1979	33%	55%	60%	47%		75%	
1980-1989	80%	100%	14%	45%	0%	55%	
after 1989	0%			100%			
average*	68%	56%	70%	50%	68%	57%	86%

*Share also includes cases from age groups where the total number was below 5 per age group.

Table 14. Reliability of visual inspection in detecting moisture and mould damage to different structures (Annila & Lahdensivu, 2020)

	Intermediate floors		Partition walls	Slab-on-ground	Ground floor with crawl space	
	Concrete	Timber			Concrete	Timber
Before 1950	63%	67%	75%	92%		55%
1950-1959	82%		76%	78%	50%	
1960-1969	100%		86%	88%	80%	
1970-1979	92%		67%	96%	100%	
1980-1989	67%		77%	88%	75%	
after 1989	100%		100%	83%		
average*	84%	60%	78%	88%	80%	65%

*Share also includes cases from those age groups where the total number was below 5 per age group.

The correlation between the reliability of visual inspection and the need to repair moisture and mould damage is important. The worst case is when reliability is low, but the repair need is high. This means that the building stock has much damage, which can be detected only by thorough moisture performance assessment and by dismantling structures. Figure 28 shows the correlation between repair need and the reliability of visual inspection (Annila & Lahdensivu 2020). In Figure 28 the repair need based on a previous study (Annila et al. 2018).

The lowest reliability values are in structures where repair need is rare. As Article II (Annila et al. 2017) points out, variations between buildings are significant when moisture and mould damage to structures is under close scrutiny. When the need for repair decreases, the influence of a single case of damage and a single building increases. This is shown in Figure 28 with low values of repair need (< 30%).

The correlation coefficient is 0.244 and coefficient of determination R^2 is 0.059 (5.9%). These quite low values are expected due to hidden damage, which is still hidden even though the number of cases of damage is high.

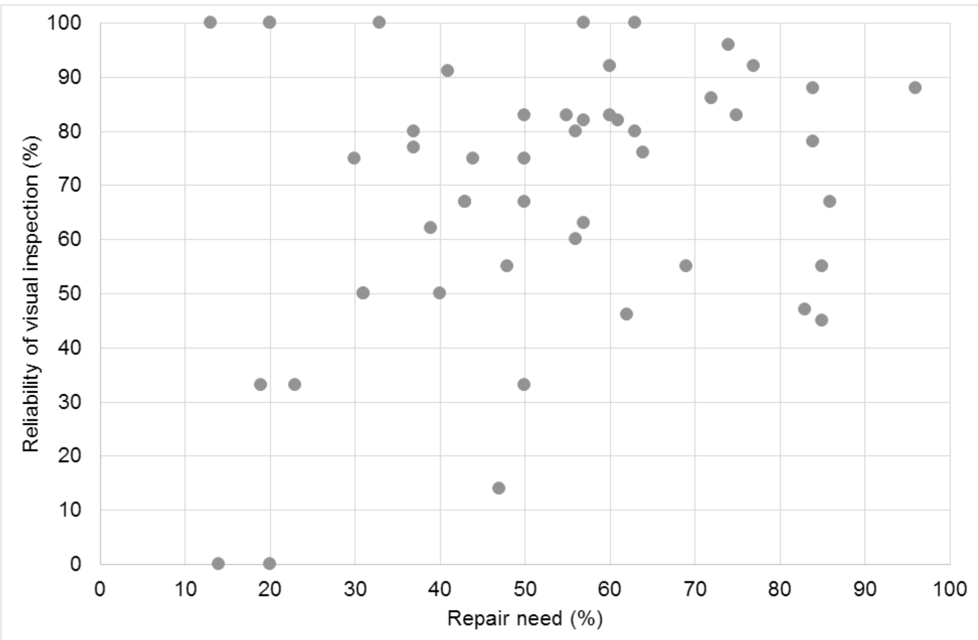


Figure 28. Correlation between repair need and the reliability of visual inspection (Annila & Lahdensivu 2020).

Figures 29, 31, 34 and 35 show the correlation between the need to repair moisture and mould damage and the reliability of visual inspection. External walls in log buildings, wooden intermediate floors and wooden ground floors are not presented in the figures due to the scarcity of data, as can be noted from Tables 13 and 14.

In ridge roof structures (Figure 29), the repair need is quite low, below 41%, in all age groups. The reliability of visual inspection rises to 91% and the trend is in right direction: when the repair need rises, so does the reliability. In flat roofs (Figure 29), the situation is the opposite: the repair need rises to 48% and, at same time, the reliability of visual inspection decreases to 55%. The difference between these two structures is a consequence of the possibilities of detecting damage from inside the structure, as illustrated in Figure 30. The dismantling of structures is needed if the extent of moisture and mould damage in a flat roof is under examination.

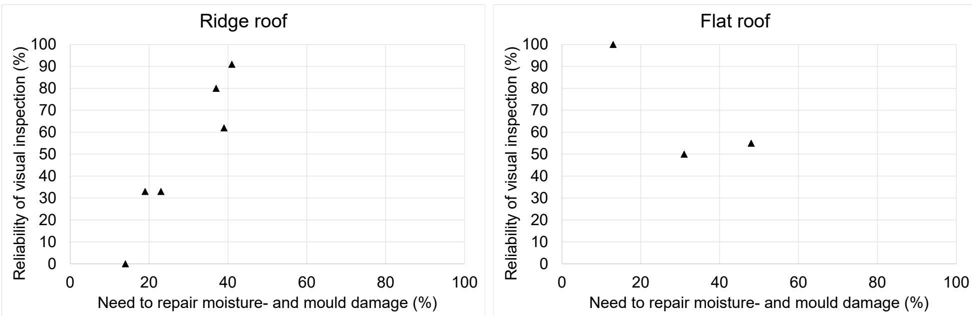


Figure 29. Correlation between repair need and the reliability of visual inspection in roof structures (Annila & Lahdensivu, 2020).

Figure 30. Inside the flat roof (left picture), there is not much space for a condition inspector to check the whole structure, so the reliability of detecting damage is lower than in ridge roofs.

In external walls (Figure 31), the type of structure greatly affects the reliability of detection. In concrete and timber-frame buildings, the material most sensitive to mould growth, typically thermal insulation, is located inside the structure, so the condition of that layer is usually impossible to detect without dismantling the structure, as shown in Figure 31. The lowest reliability values therefore decrease to as low as 45% in concrete buildings and 33% in timber-frame buildings.

In masonry buildings and walls in soil contact, the most sensitive material may be a layer of thermal insulation but, in these structures, the effect of moisture is usually also transmitted to the inner surface of the structure. Some examples of damage to external walls are presented in Figures 32 and 33.

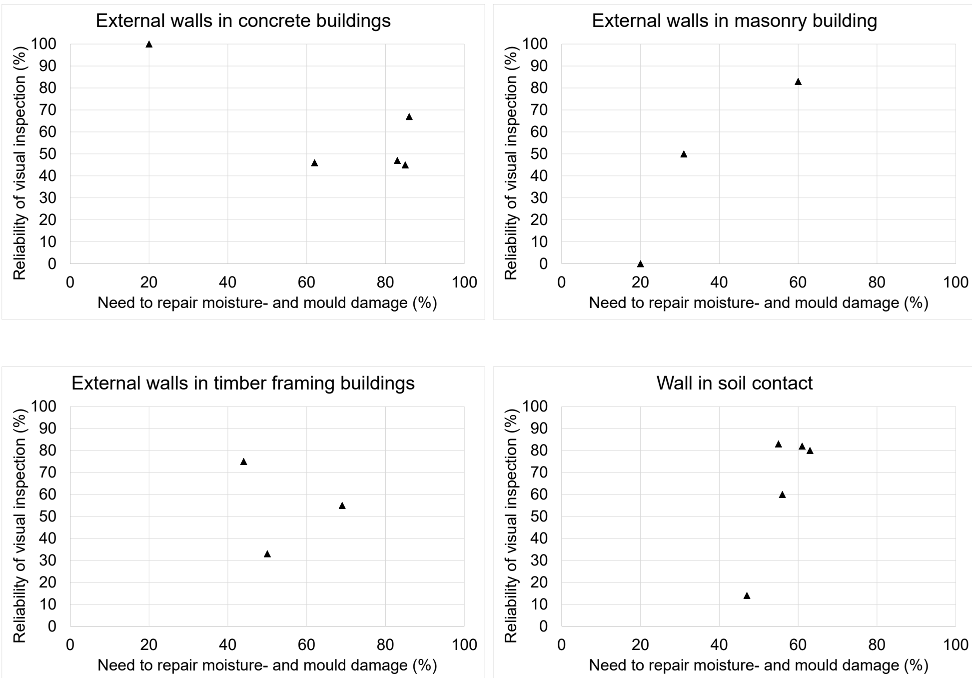


Figure 31. Correlation between repair need and the reliability of visual inspection in external walls (Annila & Lahdensivu, 2020)

Figure 32. Dismantling of structures is usually necessary to detect moisture and mould in timber-frame buildings.

Figure 33. Examples of moisture and mould damage in a masonry wall and in a wall in soil contact.

In slab-on-ground structures, high moisture content usually exists in concrete slabs and leads to damage to surface materials, but can at least be detected with a surface moisture detector. The reliability of visual inspection is therefore high in slab-on-ground structures, as presented in Figure 34.

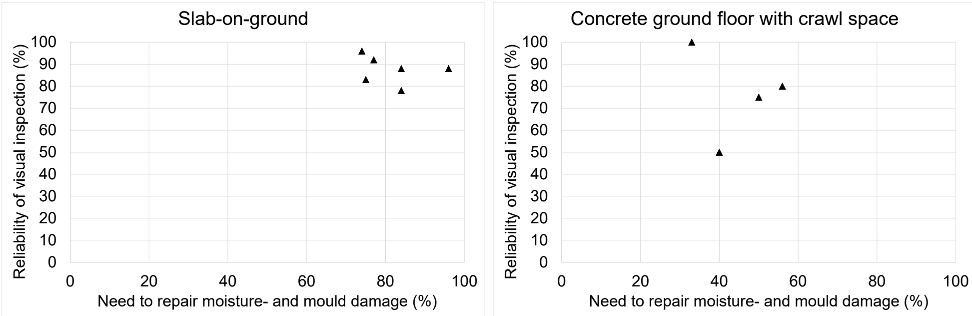


Figure 34. Correlation between repair need and the reliability of visual inspection in ground floor structures (Annila & Lahdensivu, 2020)

Partition walls are usually the simplest structures in buildings, so the reliability of visual inspection is high 67-100% as shown in Figure 35. In concrete intermediate floors, the actual structure type has a great influence on the reliability. In solid in-situ slabs and element slabs, the reliability is higher than in older structures, which may contain organic materials.

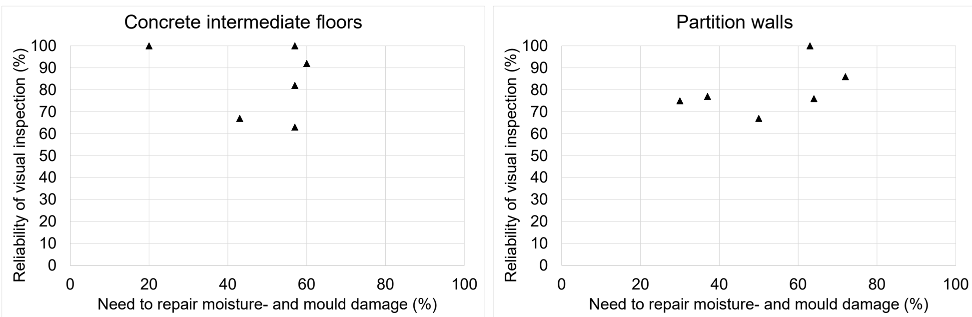


Figure 35. Correlation between repair need and the reliability of visual inspection in intermediate floors and partition walls (Annila & Lahdensivu, 2020)

It is probable that not all separate cases of damage get detected by visual inspection. However, if the main aim of visual inspection is to analyse many buildings and determine their need for repair, visual inspection is a useful method for maintenance. For example, if you find moisture and mould damage in one classroom of a school building, you have then noticed that there may be moisture and mould damage issues in the building, which should be examined more precisely by thorough moisture performance assessment.

4.4 Practical applications

The results of the thesis and articles I-IV (Annila et al. 2016, 2017 and 2018, and Annila & Lahdensivu 2020) may be utilised in practice in many ways. Table 15 includes four buildings and four basic properties of these buildings. The buildings are hypothetical but typical of Finnish building stock. The aim of this study is to point out that, just by knowing a few basic facts about buildings, it may be possible to discover major differences between buildings and to determine the probability of their being moisture- and mould-damaged. This kind of analysis may be utilised by large property owners.

Table 15. Basic properties of four hypothetical public buildings in Finland.

Building	Construction year	Roof type	Material of vertical load bearing frame	Number of floors
1	1980	flat	masonry	1
2	1960	ridge	concrete	3 + basement
3	1989	ridge	timber frame	1 + basement
4	1940	ridge	masonry	3 + basement

Table 16 present estimates of moisture and mould damage to these buildings. The number of damaged structures is based on Equation 1, and the probability of damage on the results of Article III (Annila et al. 2018). The results in the table are highlighted in colours. The study indicates in which structures moisture and mould damage are most probable and makes it possible to compare buildings to each other. This cannot be based only on construction years. The values are not exact estimates of the probability of damage because the data include only damaged buildings.

In building 2, the estimated number of moisture- and mould-damaged structures is lower than in building 4 but, in almost every structure, the probability of damage is higher in building 2 than in building 4. Building 2 may therefore be considered to be riskier for moisture and mould damage than building 4, even though it is 20 years younger.

The risk level of building 3 is between buildings 2 and 4. Moreover, the probability of damage between buildings 2 and 3 is quite similar, even though their basic properties differ significantly from each other. The lowest risk of moisture and mould damage is in building 1.

It may be reasonable to highlight damage to different structures differently and many different factors affect to this, which is why the topic needs further research and development before it can be widely used as a finished method. One example is basements, which may be only technical or storage spaces in public buildings. This is why damage to these basements may not have the same negative effect on indoor air quality or occupants' health as damage in other spaces or structures does.

Table 16. Estimated number of damaged structures and the probability of damage in certain structures.

Building	Estimated number of damaged structures	Probability of damage (%)					
		Roof	Slab-on-ground	External wall	Wall in soil contact	Intermediate floor	Partition walls
1	3,1	13	84	20	0	0	37
2	3,8	39	96	62	55	57	72
3	2,7	37	84	69	47	43	37
4	4,6	41	77	31	61	57	30

Estimated number of moisture and mould damaged structures

0	1	2	3	4	5	6	7

Probability of moisture and mould damage (%)

0	10	20	30	40	50	60	70	80	90	100

Damage to many buildings may be estimated by statistical data, but examination of individual building should be based on thorough moisture performance assessment.

Another significant factor when comparing public buildings to each other from a perspective of moisture and mould damage is to know how easily damage may be detected. Table 17 presents the reliability of early detection based on the results of Article IV (Annila & Lahdensivu 2020). Table 17 includes the same four hypothetical buildings as above.

Table 17. Reliability of the early detection of moisture and mould damage in different structures.

Building	Reliability of early detection (%)					
	Roof	Slab-on-ground	External wall	Wall in soil contact	Intermediate floor	Partition walls
1	100	88	0	100	100	77
2	33	88	46	83	100	86
3	80	88	55	14	67	77
4	91	92	50	82	63	75

Reliability of early detection (%)

0	10	20	30	40	50	60	70	80	90	100

The detection of moisture and mould damage in external walls, walls in soil contact and roof structures varies greatly between these four hypothetical public buildings. The risk of moisture and mould damage is lowest in building 1 as presented before (see Table 16) but, at the same time, it should be noted that the probability of detecting moisture and mould damage in an external wall without a thorough moisture performance assessment is lowest in these four structures. This structure should therefore be monitored more carefully in the normal maintenance of the property. In building 2, this most risky structure is the roof, and in building 3 the wall in soil contact.

5 CONCLUSION

5.1 The outcomes of the research

The results of this thesis indicate that the risk of moisture and mould damage to different structures in many buildings can be estimated with statistical data formed from moisture performance assessments and the damage history of the buildings. However, the results and findings clearly indicate a large scatter between damage to individual buildings, so the need to repair moisture and mould damage cannot be based only on statistical data.

The importance of thorough moisture performance assessments was also confirmed from other perspectives. The extent of moisture and mould damage is probably more point- sized than widespread, and it is probable that damage appears simultaneously in many structures. Moreover, in certain structures moisture and mould damage are also more often hidden, which makes it more difficult to detect all moisture and mould damage. If the number of structural openings is too low, it is possible that damage to the structures will not be detected by moisture performance assessment.

A risk assessment based on statistical data helps to identify the buildings in the building stock where the probability of moisture and mould damage is highest. At the same time, this assessment highlights those structures in every building where damage is most often hidden. Furthermore, this knowledge helps us to focus on risk structures in the maintenance of buildings, so the condition of these structures may be followed more precisely.

After the high risk of moisture and mould damage has been identified in buildings, a light visual inspection can be used to gather more data about the building and confirm the condition of different structures. Data analyses and visual inspections contribute to the initiation of thorough moisture performance assessments as soon as possible after moisture and mould damage occurs, which helps to prevent indoor air quality problems. A recommendation to regularly carry out visual inspection can be made based on the results of this thesis.

5.2 The need for further research

Indoor air quality problems, indoor air impurities and moisture and mould damage are complex problems that require extensive scientific research before they can be sufficiently managed. Based on this thesis, the following research topics are highlighted as most important:

Development of inspection procedure

It is recognised that the condition inspections and assessments used have not prevented moisture and mould damage to buildings or other indoor air quality issues in Finland. An inspection protocol should be developed, which is regularly repeated in every public building. This procedure must identify the critical features of the building and assess its condition from the point of view of preventing moisture and mould damage, and other indoor air quality issues.

Reasons for moisture and mould damage

The reasons for moisture and mould damage should be studied more precisely in future. This knowledge will help in the understanding of the most common reasons for damage, and thus can be utilised to prevent damage when most critical factors are known.

The modelling of the hygrothermal behaviour of structures is a normal part of structural planning, but fault tolerance is not a basic part of this modelling. If the reasons for damage are known more precisely, this will help to set standards for modelling, and there could be increased fault tolerance to prevent the risk of moisture and mould damage in new and renovated buildings.

Moisture and mould damage to the building stock

Moisture and mould damage to the entire building stock should be examined more precisely. Previous studies have usually been based only on buildings with indoor air problems. Reference buildings have not been widely examined with thorough moisture performance assessments. If reference buildings are included in the research material, investigation of the condition of buildings is usually based on questionnaires filled in by occupants who are not professionals in the condition of buildings, so estimates of the condition of the building stock are not very accurate in Finland at the moment.

Detection of other indoor air impurities

The typical indoor air quality problems in Finnish public buildings are a consequence of many different indoor air impurities, so repairing only moisture and mould damage to structures will not ensure healthy indoor air conditions. The detection of other indoor air impurities should therefore also be studied in greater depth in future.

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Practical experiences from several moisture performance assessments

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Practical Experiences from Several Moisture Performance Assessments

Petri J. Annila, Jukka Lahdensivu, Jommi Suonketo and Matti Pentti

Abstract This study analysed the moisture performance assessment reports of 76 buildings: 56 schools, nine healthcare buildings, three daycare centres and five office buildings. The researchers' practical experiences from moisture performance assessments were also made use of in the study. The aim of this study was to determine the methods used to detect moisture and mould damage in the building stock. The results of the study show that most moisture and mould damage is detected by a surface moisture indicator (Annila et al. in Proceedings of the 1st international symposium on building pathology, pp 115–122, 2015a). That is an important finding since these indicators enable easy measuring of large sections of structures and targeting of more detailed inspections, moisture measurements and material samplings based on mapping with them.

Keywords Indoor air quality · Moisture · Mould · Sick building syndrome · Condition assessment

1 Introduction

The indoor air quality (IAQ) problems of the building stock are caused by many factors including carbon dioxide (CO_2), carbon monoxide (CO), nitrogen dioxide (NO_2), particular matter (PM), high indoor temperature and relative humidity, low

P.J. Annila (✉) · J. Lahdensivu · J. Suonketo · M. Pentti
Department of Civil Engineering, Tampere University of Technology,
P.O. Box 600, 33101 Tampere, Finland
e-mail: petri.annila@tut.fi

J. Lahdensivu
e-mail: jukka.lahdensivu@tut.fi

J. Suonketo
e-mail: Jommi.suonketo@tut.fi

M. Pentti
e-mail: matti.pentti@tut.fi

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petri.annila@tut.fi

ventilation rate, mould, bacteria, volatile organic compounds (VOC), chemicals, dust, cigarette smoke, pet allergens, radon, asbestos and formaldehyde (HCHO). The most significant factor varies by region and year of construction (Weschler 2009). In the Nordic countries and in North America, indoor air problems are often related to moisture and mould damage in structures and buildings (Bornehag et al. 2001, 2004; Hyvärinen 2002; Mudarri and Fisk 2007).

A recent study (Annila et al. 2015a) established the methods used in Finland to detect moisture and mould damage in buildings and structures. The research material consisted of moisture performance assessment reports on 76 buildings. Moreover, experiences from practical moisture performance assessments were used to find new targets of development. The study was conducted as part of wider research aimed at developing operating procedures and methods for earlier detection of moisture and mould damage. The methods can help prevent moisture and mould damage and ensuing IAQ problems and negative health impacts.

2 Literature Review

2.1 Moisture Performance Assessment in Finland

Awareness of moisture and mould damage in the building stock and its impact on IAQ and the health of users increased in the 80s. Subsequently, the subject area was researched a lot and the methods presently used in Finnish moisture performance assessment became established in the 90s. They are partly described, for instance, in Haverinen-Shaughnessy et al. (2008) and Asikainen (2008). An updated guide for moisture performance assessment is currently being prepared as part of the moisture and mould programme of the Ministry of the Environment in Finland.

In Finland, research on moisture and mould damage is referred to either as moisture performance assessment or IAQ research. In practice, their contents are nearly identical, but their aims are different. Moisture performance assessment determines the current condition of structures, any possible damage in them, and their future repair needs. Indoor air research focuses on IAQ and possible impurities in the air. High quality indoor air research, however, also establishes the moisture and mould damage to structures which makes its content practically identical to that of a moisture performance assessment.

Moisture performance assessments generally consist of the four main phases described in Fig. 1 (Annila et al. 2015a): analysis of background and input data, field study, necessary laboratory tests, and analysis and conclusions.

petri.annila@tut.fi

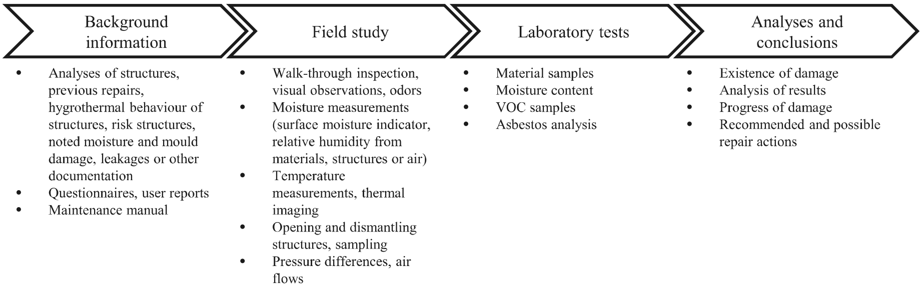

Fig. 1 Four main phases of moisture performance assessment and their main content (Annila et al. 2015a)

2.2 *Initiation of Moisture and Mould Damage*

Moisture and mould damage and the ensuing indoor air problems and repair need are described in Fig. 2. Damage to structures is initiated by moisture stress. There is wide variation between moisture sources and levels of moisture stress. When moisture stress is sufficiently high and lasts long enough, the capacity of a material subject to moisture stress may be exceeded leading to moisture damage. Depending on the material's properties and prevailing conditions, the moisture in a structure may further lead to mould damage. The moisture stress and time required for mould growth can be estimated by different mould growth models (Vereecken and Roels 2012; Ojanen et al. 2010; Vinha et al. 2013; Johansson et al. 2005, 2012; Sedlbauer 2002).

Depending on the prevailing conditions, the material layers of a structure, air flows and location of mould damage, impurities may spread from a damaged area into indoor air leading to an indoor air problem and possible health symptoms in users. Due to the complexity of the phenomena, the links between concentrations of indoor air impurities and health symptoms have not been determined, but the correlation between them is clear (Bornehag et al. 2001, 2004).

Usually, only health symptoms of users lead to moisture performance assessments or indoor air studies that determine the repair need of a building.

The period between the various phases is typically very long. Asikainen (2008) estimated that repairs are typically undertaken 2–5 years after the occurrence of health symptoms. Even after repairs, it takes 6–12 months for indoor air conditions to stabilise (Haverinen-Shaughnessy et al. 2008). Thus, depending on the occupancy of the building, the users can be exposed to impurities for quite long periods even after IAQ problems or moisture and mould damage have been identified.

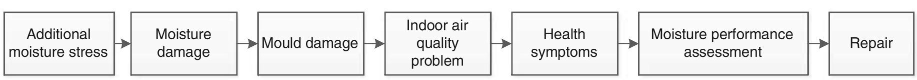

Fig. 2 Development of moisture and mould damage and related repair need

Consequently, there is a clear need for more effective procedures that enable faster identification of moisture and mould damage.

2.3 Extent of Moisture and Mould Damage in Buildings

The extent of moisture and mould damage in the building stock has been the subject of many studies, for instance, in Canada (Lawton et al. 1998), Finland (Nevalainen et al. 1998), Sweden (Smedje et al. 1997), Austria (Haas et al. 2007) and Norway (Holme et al. 2008). The results have also been published in scientific journals. Zock et al. (2002) studied the link between moisture and mould damage and asthma in 18 countries, in Europe and elsewhere. Undoubtedly many national studies, whose results have not been presented in English-language scientific journals, have also been conducted. Several studies made in Finland have also been aimed at decision makers, not scientific circles. A comprehensive summary of these Finnish studies was prepared in 2012 (Reijula et al. 2012). An abstract of it is available in English.

Reijula et al. (2012) summarised the major moisture and mould damage occurring in the Finnish building stock as follows: *We estimate that the prevalence of significant damp and mould damage is 7–10 % of the floor area in small and row houses, 6–9 % in multi-storey apartment block, 12–18 % in schools and kindergartens, 20–26 % in care institutions and 2, 5–5 % in offices.*

Although the extent of moisture and mould damage has been examined in several studies, their results are not mutually comparable since the research methods and definitions of moisture and mould damage have varied. Many studies have investigated the extent of moisture and mould damage through questionnaires directed at users (Lawton et al. 1998; Nevalainen et al. 1998; Haas et al. 2007; Holme et al. 2008; Zock et al. 2002). Questionnaires have been complemented for instance by visual observations made by professionals (Lawton et al. 1998; Nevalainen et al. 1998; Haas et al. 2007; Holme et al. 2008), measurements (Lawton et al. 1998) and indoor air samples (Lawton et al. 1998; Haas et al. 2007; Holme et al. 2008). Comparison of these research methods to the thorough Finnish moisture performance assessment of Fig. 1 makes the difference between the methods apparent.

Studies have shown that a significant part (Partanen et al. 1995), up to one-third (Pirinen 2006), of moisture and mould damage may be hidden, that is, not detectable on the surface of structures despite being examined by an expert. Thus, studies of moisture and mould damage to the building stock based on user surveys and partial measurements are not accurate. It is possible that some damage has gone unnoticed which may accentuate the significance of observable damage in such studies where hidden damage may be totally ignored (Asikainen 2008). Yet, visual observations and user reports on moisture and mould damage play a major role in damage identification and moisture performance assessment (Leivo et al. 1998).

Due to the variance in research methods and questions, the picture of the present state of the building stock and its moisture and mould damage is inaccurate. Lawton

petri.annila@tut.fi

et al. (1998) stated in the 90s that information about the condition of a building is the most important factor when planning its repair. The same observation was made in connection with a study on the moisture and mould damage repair projects of Finnish municipalities (Kero 2011). Inadequate moisture performance assessments have led to many failed repair projects (Kero 2011).

A recent study (Annila et al. 2015b) showed that Finnish buildings suffering from indoor air problems often have multiple problems, that is, moisture and mould damage in several structures. In the study the structures were divided into six groups: base floors, roof assembly, intermediate floors, external walls, walls in soil contact and partitions. All examined buildings did not have intermediate floors and walls in soil contact. 68 % of the examined buildings had moisture and mould damage in at least three different structural elements such as the base floor, the roof assembly and an external wall. It was also discovered that individual damaged spots were quite small in area (Annila et al. 2015b).

Thorough moisture performance assessments are necessary to avoid failed repairs (Lawton et al. 1998; Kero 2011; Marttila 2014). Most important from the viewpoint of successful repairs is to know all existing damage despite it being spread across several structures (Annila et al. 2015b) and partly hidden (Partanen et al. 1995; Pirinen 2006). For this reason, more effective identification of moisture and mould damage and development of moisture performance assessment are still topical research areas.

2.4 *Definition of Moisture and Mould Damage*

For the purposes of this study (Annila et al. 2015a), any damage that meets at least one of the following criteria was considered moisture and mould damage (Annila et al. 2015b):

I Mould damage visible to the naked eye without magnification.
II Unrepaired, active water leakage detrimental to the structure or building material that it wets.
III A structure or building material found to be moist, extremely moist or wet by a surface moisture detector based on a five-step assessment scale: dry, slightly moist, moist, extremely moist and wet.
IV Relative humidity of the structure exceeds 80 % in a drill-hole measurement.
V A material sample shows active microbial (fungal or bacterial) growth. The fungal and bacterial colonies are determined by dilution plating on MEA agar and TYG agar.

Criterion I
The occurrence of moisture and mould damage has been examined in several scientific studies based on sensory observations (e.g. Lawton et al. 1998; Nevalainen et al. 1998; Smedje et al. 1997; Haas et al. 2007; Holme et al. 2008; Zock et al. 2002). In a summary of the Finnish building stock (Reijula et al. 2012),

petri.annila@tut.fi

many of the original studies are also based, at least partly, on visual observations of damage in buildings. That research method was considered scientific enough for the purposes of these studies.

The observations of TUT researchers about moisture performance assessments support the assumption that moisture and mould damage can be so clearly visible to the naked eye on the surface of a structure or through an inspection opening without a magnifying glass or microscope that establishment of damage requires no more detailed studies. Figure 3 shows an example of clearly visible mould damage on a chipboard wall. Verbally described observations in moisture performance reports are often illustrated by photos which also allow the reader to see what the target of observation looked like during field study.

Olfactory observations by a condition investigator were not used as a criterion of moisture and mould damage in this study because the existence of a strong mould odour in a space does not necessarily indicate reliably which structure in the said space is damaged. Air flows and leaks can carry odours from other spaces.

Criterion II

Water leaks, which may occur both in pipes and structures, have been made into a separate criterion among visual observations. These leaks have not necessarily led to moisture or mould damage by the time of the moisture performance assessment, but an unrepaired leak is highly likely to damage structures and materials. Thus, repair of observed leaks is as important as that of observed existing moisture and mould damage. Figure 4 shows an example of a leaky roof assembly.

Criterion III

Nevalainen et al. (1998) used surface moisture measurements in their study on moisture and mould damage. The mapping made in TUT moisture performance assessments using a surface moisture indicator was the basis of dividing structures into five classes: dry, slightly moist, moist, extremely moist and wet. Similar classification is used in Finland quite generally. In many moisture performance

Fig. 3 Example of visually observed mould damage to a chipboard structure

petri.annila@tut.fi

Fig. 4 Example of leak in a roof assembly detected during a moisture performance assessment

assessment reports analysed for the study, the results of surface moisture measurements had been complemented with more accurate moisture measurements of structures, which allows comparison of the results of surface moisture measurements and more accurate moisture measurements. The combination of the observations of TUT researchers and performed measurements constitute a reliable method properly used for determining the moisture content of structures although surface moisture measurements do not yield an accurate numerical value.

Criterion IV
The moisture and mould damage in structures and the building materials they contain can be modelled by different mould growth models. Vereecken and Roels (2012) have compared the different models that allow estimating the conditions and speed at which structures develop mould damage. Table 1 shows the mould growth sensitivity classes of the VTT-TUT mould growth model often used in Finnish studies (Ojanen et al. 2010, 2011; Vinha et al. 2013).

Johansson et al. (2005, 2012) have suggested critical moisture contents for various materials at which mould growth is possible. The sensitivity of materials to mould growth based on those critical contents is similar to that of the classification of Table 1. For instance, Johansson et al. (2012) determined that the critical moisture content of pine is 75–80 % RH and that of cement-based boards 90–95 %

Table 1 Mould growth sensitivity classes (Ojanen et al. 2010, 2011; Vinha et al. 2013)

Sensitivity class	Materials
Very sensitive	Sawn spruce and pine, planed pine, pine sapwood
Sensitive	Planed spruce, gluelam board, paper-coated PUR, gypsum boards, paper-based products
Medium resistant	Carbonated concrete, aerated and cellular concrete, glass wool, polyester wool, cement-based products
Resistant	Polished PUR, glass, metals, fresh alkali concrete

petri.annila@tut.fi

RH. Their material is based on an earlier publication used in several studies after the original one (Johansson et al. 2005). Sedlbauer (2002) also presented similar substrate categories for building materials.

Based on a summary of the mould growth models (Ojanen et al. 2010, 2011; Vinha et al. 2013; Johansson et al. 2005, 2012; Sedlbauer 2002), mould growth in the most sensitive materials, such as organic building materials, is possible at about 80 % RH at normal temperature of the structures.

A survey of the typical structures found in the Finnish building stock shows that the structures themselves or their component materials fall into the two most sensitive classes of Table 1. Therefore, the critical value of 80 % RH was used in this study to assess Finnish structures.

Criterion V
Material samples detached from building materials can be used with the direct culture or diluted culture method to determine whether there is microbial (fungal or bacterial) growth in the sample. The fungal and bacterial colonies were determined by dilution plating on MEA agar (20.0 g of malt extract, 20.0 g of saccharose, 1.0 g of peptone, 20.0 g of agar, and 0.1 g of chloramphenicol in 1 l of deionized water) and TYG agar (5.0 g of tryptone, 2.5 g of yeast extract, 1.0 g of glucose, 15.0 g of agar, and 0.5 g of cycloheximide in 1 l, of deionized water). The colonies were counted on day 7 (fungal) and day 10 (bacterial) after incubation. The fungal genera were identified microscopically. Furthermore, bacteria were classified as actinomycetes and other bacteria. This is a customary material sample analysis method in Finland (Pessi et al. 2002).

3 Research Materials and Methods

3.1 Research Material

Researchers at TUT Department of Civil Engineering have performed moisture performance assessments of 76 municipality-owned buildings: 59 schools, nine healthcare buildings, three daycare centres and five office buildings. The originally independent studies were later summarised in various ways. Users of all examined buildings have had different health symptoms and other negative sensations of poor IAQ. In the case of 49 buildings, the date of completion of the plan for the moisture performance assessment, the field study and reporting could be determined.

The studied buildings represent well the age distribution of the Finnish building stock. The oldest individual buildings had been built in the 1800s while the majority had been completed in the 50s, 60s and 70s—the period when school construction was especially brisk in Finland. The age distribution of the research material is shown in Fig. 5. The research material included all conventional structures, building materials and building systems used in Finland.

petri.annila@tut.fi

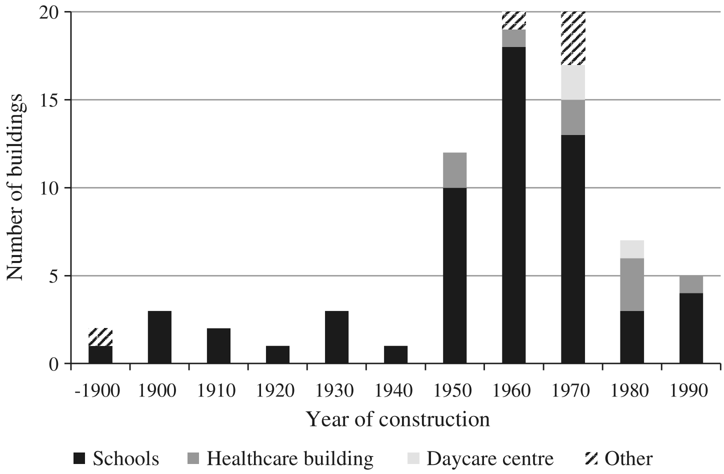

Fig. 5 Age distribution of examined buildings (Annila et al. 2015a)

3.2 Research Method

The 76 buildings of the study were originally examined as individual units. However, the content of the moisture performance assessments had been the same with all buildings (as shown in Fig. 1). At the outset of the study, the content of the moisture performance assessment reports on the 76 buildings, especially as concerns moisture and mould damage, was transferred to a database. All observed moisture and mould damage mentioned in the reports including related basic data, such as structure, material and used research methods, was entered. Basic data of each building such as year of construction, material of bearing frame, occupancy, location, time of assessment, number of storeys, roof type and foundation method were also recorded.

A total of 1784 observations suggesting moisture and mould damage had been made about the studied buildings. After their recording, observations were classified into two groups: "0 = undamaged" and "1 = damaged" based on the below definition of acute moisture and mould damage. An observation was classified as acute moisture and/or mould damage (class 1 = damaged) if it met at least one of the following criteria (Annila et al. 2015b):

I Mould damage visible to the naked eye without magnification.
II Unrepaired, active water leakage detrimental to the structure or building material that it wets.
III A structure or building material found to be moist, extremely moist or wet by a surface moisture detector based on a five-step assessment scale: dry, slightly moist, moist, extremely moist and wet.

petri.annila@tut.fi

Table 2 Basic structure of the database and four examples

Example	Visual observation	Active leakage	Surface moisture detector	Relative humidity	Mould growth	Class: undamaged or damaged
1	Discolouration		Dry			0
2	Paint peeling off		Moist	86.3 % RH		1
3	Discolouration		Extremely moist		Actinomycetes	1
4	Visible damage	Yes				1

IV Relative humidity of the structure exceeds 80 % in a drill-hole measurement.
V A material sample shows active microbial (fungal or bacterial) growth. The fungal and bacterial colonies were determined by dilution plating on MEA agar and TYG agar.

Table 2 shows examples of entries in the database. They are related to observations and measurements made in the buildings to detect moisture and mould damage in structures.

The examples in Table 2 may correspond, e.g., to observations like the following.

1. The wall surfacing material had discolouration that was dry according to the surface moisture indicator. The discolouration was the result of normal soiling of the structure.
2. The coat of paint on the wall in soil contact was peeling off. Drill-hole measurements on the concrete structure indicated a moisture content of 86.3 % RH.
3. Moisture stains were visible in the ceiling and the structure was extremely moist according to the surface moisture indicator. A material sample from the roof assembly showed strong growth of actinomycetes.
4. The partition had visually observable damage around a leaking tap water pipe.

Of the above described observations and those presented in Table 2, nos. 2, 3 and 4 have been classified as damage in accordance with the used acute moisture and mould damage definition.

3.3 Scope of the Study

The study was limited to moisture and mould damage occurring in structures. A similar approach was followed also in the original moisture performance assessments. They examined what types of damage occur in structures and their repair need.

petri.annila@tut.fi

Moisture and mould damage has been found to have a negative impact on the health of users (Bornehag et al. 2001, 2004). The 76 moisture performance assessment reports used as research material did not, however, focus on the health symptoms experienced by users, which is why this study also excludes them. The original moisture performance assessment reports also dealt with ventilation and shortcomings and observations related to its performance. Yet, this study excludes building systems.

The scope of the study is based on the following hypothesis: When all moisture and mould damage in structures is repaired, the building cannot cause any health symptoms or indoor air problems related to moisture and mould damage to structures.

4 Results

4.1 Length of Moisture Performance Assessment Process

Different mould growth models (Vereecken and Roels 2012; Ojanen et al. 2010; Vinha et al. 2013; Johansson et al. 2005, 2012; Sedlbauer 2002) can be used to estimate the time required for mould damage to occur. Generally it is weeks, even months, depending on the level of moisture stress and the sensitivity of a material to mould growth.

Presently, there is not sufficient research data on how quickly and what types of mould damage spread impurities into indoor air which may cause health symptoms in users. The spreading is influenced by many factors such as pressure ratios, location of damage, materials of structure and air flows. Moreover, people react differently to spreading impurities. TUT has conducted user surveys and interviewed building users in connection with moisture performance assessments. According to users, health problems have generally continued for quite long before investigation of the cause of symptoms and the building's condition has started.

The analysed moisture performance assessment reports have been used to determine the time between (1) the start of planning the research and the first day of field study, (2) the start of field study and reporting, and (3) the start of planning the study and reporting.

The length of the first period indicates the slowness of municipal decision-making processes although the users experience health symptoms related to a building. The length of the second period indicates the time taken by a moisture performance assessment. The third criterion represents the length of the overall process, being the sum of the two previous ones. Figure 6 shows the length distribution of these three periods for the 49 buildings for which the data in question could be determined.

In the case of 31 (63.3 %) buildings, the moisture performance assessment was launched within 2 months of submission of tender. The moisture performance assessment proper including reporting may take several months: according to the study material, the shortest time it took to write the report was 1–2 months after the field study. A total of five (10.2 %) condition assessments were completed that

petri.annila@tut.fi

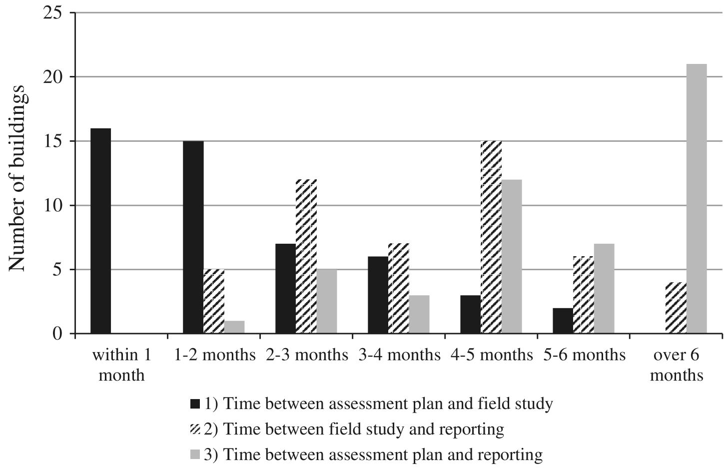

Fig. 6 Lengths of different phases of moisture performance assessments in research data

quickly. The period between the planning and reporting of the assessment was over six months in the case of 21 buildings (42.9 %).

Asikainen (2008) found that it can take 2–5 years between the occurrence of health symptoms and the completion of repairs. In addition, Haverinen-Shaughnessy et al. (2008) found that it takes 6–12 months after repairs for the impurity content to stabilise.

Due to the slowness of the processes, the exposure times to indoor air impurities caused by moisture and mould damage are long. Therefore, there is a clear need to develop moisture and mould damage detection methods so that damage can be observed more effectively before health symptoms appear.

4.2 Detection Methods

Based on the used criteria, a total of 920 observations on acute moisture and mould damage were made in the examined 76 buildings. The number of detected damage was great since the moisture performance assessments examined the extent of damage to determine the extent of required repairs. Thus, for instance, the base floor may have been investigated from different spaces whereby several observations about moisture and mould damage in an individual structural element of a building may have been made.

Figure 7 shows the distribution of observed moisture and mould damage in examined buildings by structures.

Figure 8 shows the methods used to detect the 920 moisture and mould damage in question. Part of the damage was detected by several methods, for example, surface moisture measurement and material samples. A single method was used to

petri.annila@tut.fi

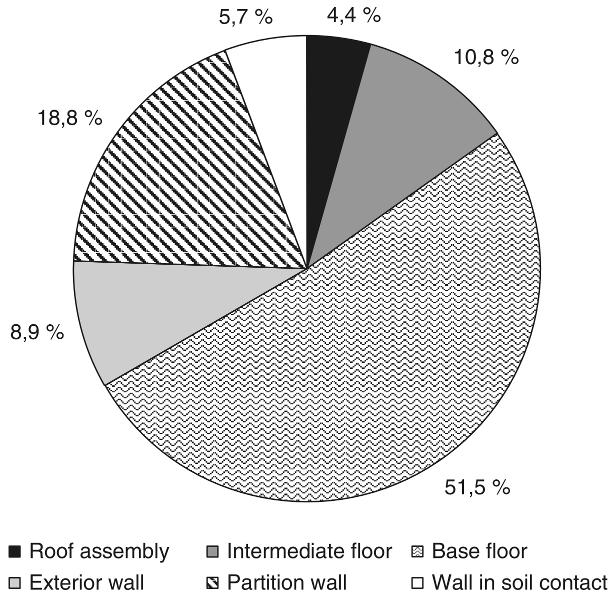

Fig. 7 Locations of moisture and mould damage by structures

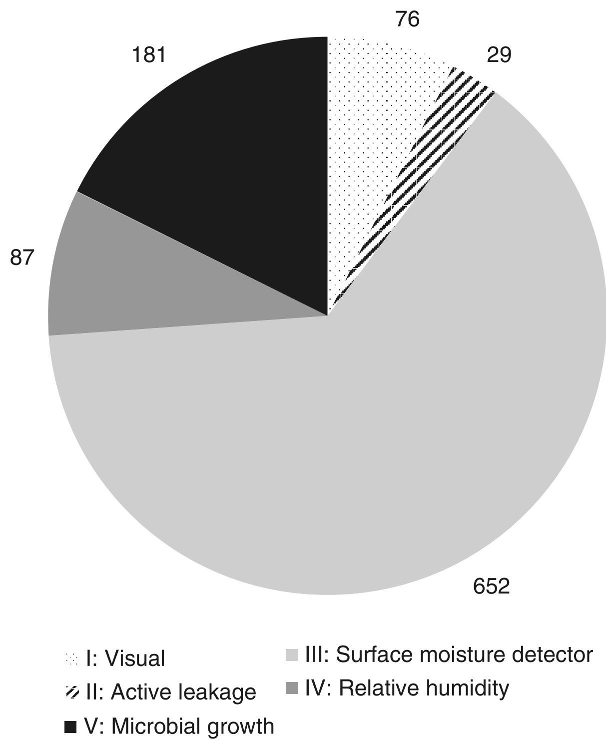

Fig. 8 Methods used to detect moisture and mould damage

petri.annila@tut.fi

Table 3 Methods used to detect moisture and mould damage

Detection method	Number of detections	Share of all detections (%)	Confirmed measurements or observations (%)
I Visual: clear damage	76	7.4	47.4
II Visual: active leakage	29	2.8	13.8
III Surface moisture detector	652	63.6	12.1
IV Relative humidity	87	8.5	34.5
V Material sample test	181	17.7	30.4

detect 821 (89.2 %) damage while two or more methods were used for the other 99 (10.8 %).

The number of confirmed measurements and observations (99 damage) is small. This is due to the fact that measurements at one spot are rarely made by several methods. For example, if damage is suspected in the base floor, the moisture content of the structure can be measured from a different spot than the material sample taken. If both methods indicate damage in the base floor, the base floor of the space in question has two damaged areas according to the calculation method, the existence of neither having been confirmed by the other. When the base floor is examined as a unit, more confirming measurements are made, but at different points of the structure.

Table 3 shows the number and share of detections by different methods as well as how often measurements and observations have been confirmed by another method. According to Table 3, moisture and mould damage was detected 652 times with a surface moisture indicator. Some other method was used to confirm 12.1 % of these measurements.

Visually observed clear mould damage, RH measurements and material samples have most often been confirmed by other methods: in 47.4, 34.5 and 30.4 % of the cases, respectively. The used confirmation method has often been surface moisture measurement.

Table 3 shows that surface moisture measurements (63.6 %) are clearly the most used method for detecting moisture and mould damage. The second most popular method is material samples (17.7 %)—the large difference between their use is due to the fact that surface moisture measurements yield a value that indicates the moisture content of a structure quickly and cost-effectively.

A total of 589 sensory observations by condition investigators had been recorded in the assessment reports on the 76 buildings involved in the study. Of these observations 258 (43.8 %) were linked to 920 detected moisture and mould damage. Moisture and mould damage could be detected by a single sensory observation in 105 instances. It is highly likely that considerably more sensory observations

petri.annila@tut.fi

Table 4 Methods used to detect moisture and mould damage in different structures

Detection method	Roof assembly (%)	Intermediate floor (%)	Base floor (%)	Exterior wall (%)	Partition wall (%)	Wall in soil contact (%)	Average (%)
I Visual: clear damage	13.3	7.5	5.7	8.8	11.5	3.5	8.4
II Visual: active leakage	13.3	0.9	2.1	0.0	0.5	1.8	3.1
III Surface moisture detector	13.3	65.4	67.9	48.4	68.8	77.2	56.8
IV Relative humidity	11.1	9.3	11.8	3.3	2.1	5.3	7.2
V Material sample test	48.9	16.8	12.4	39.6	17.2	12.3	24.5

were made in connection with field studies. If sensory observations were found to be unconnected to moisture and mould damage, they have not necessarily been entered in the moisture performance assessment report. Moreover, the sensory observation may not have been recorded either if a structure had been subjected to moisture measurements or material sample tests. Yet, the significance of an investigator's sensory observations is high.

Table 4 shows the method used to detect damage in different structures. The shown deviation between moisture and mould damage detection methods for different structures is wide.

5 Discussion

5.1 Length of Moisture Performance Assessment Process

The time from the beginning of moisture stress and the occurrence of moisture and mould damage is long in Finland. The process may take several years as found in earlier studies (Asikainen 2008). The observations of this study and that by Haverinen-Shaughnessy et al. (2008) support the view of the long duration of the process phases. In the case of the 76 moisture performance assessments included in this study, the date of completion of the condition assessment plan, the field study and the report could be established. In 21 (42.9 %) cases, the interval between the completion of the moisture performance assessment plan and reporting was over six months, 358 days at the longest.

All phases of the process need to be developed in order that repair of moisture and mould damage becomes faster and exposure of users to indoor air impurities

petri.annila@tut.fi

due to moisture and mould damage becomes shorter. Moisture performance assessments also need to be developed and studied further and the best phase for launching assessments determined. Presently, they often start only after a building's users start to show health symptoms. Yet, we should be able to act before these health symptoms occur. Early detection of moisture and mould damage and management of moisture risks require more effective methods and approaches.

The study showed that moisture performance assessments take a long time: based on the research material the period between completion of the assessment plan and the report was on average 183 days. Of that, the completion of the assessment plan and the field study took 63 days, on average, while the remaining 120 days were spent completing the report and analyses after field study.

The shortest time required for the actual moisture performance assessment process (from field study to reporting) is about one month, since the analysis of material samples generally takes at least two weeks. In the case of five buildings (10.2 % of research material), the moisture performance assessment report was finished in 1–2 months after the field study. However, the longest time required was over six months (in 4 of 49 cases). The length of the moisture performance assessment process is probably due to the fact that the results of material sample tests are not known during field study but have to be waited for. That may lead to a situation where further samples from a building are needed, which naturally doubles the time needed to complete the report.

5.2 Moisture and Mould Damage Detection Methods

Based on the research results, the sensory observations of the condition investigator and surface moisture measurements play a significant role in the detection of moisture and mould damage. That is also suggested by the fact that many studies on the damage suffered by the building stock have searched for moisture and mould damage especially by sensory observations (e.g. Lawton et al. 1998; Nevalainen et al. 1998; Smedje et al. 1997; Haas et al. 2007; Holme et al. 2008; Zock et al. 2002). An expert opinion and surface moisture measurements can indeed establish quickly and cost-effectively the repair need of buildings. It is not a novel finding since Lappalainen et al. (2001) have shown that the order of importance of school building repairs can be set based on sensory observations and surface moisture measurements.

However, an expert's observations reflect only the conditions at isolated spots of a building. The regular users of a building make observations over the long term. Leivo et al. (1998) recognised that users play an important role in the detection of moisture and mould damage. The significance of users has also been noted in studies on the damage suffered by the building stock and their impact (Zock et al. 2002; Howden-Chapman et al. 2005). The subject requires further study in order for us to know how well building users without expertise in moisture and mould damage and IAQ problems can detect related damage and risks compared to an expert.

petri.annila@tut.fi

Based on the results of this study, 73.9 % of detected moisture and mould damage could be detected from the surface of structures as clear mould damage (Detection method I), a water leak (II) or by surface moisture measurements (III). As previously stated, visual observations have probably been made in connection with moisture measurements (IV) and material sample tests (V), which were not necessarily always recorded in moisture performance assessment reports, or that by themselves were not sufficiently clear indicators of the existence of damage.

Partanen et al. (1995) found that a significant portion of the moisture and mould damage in the Finnish building stock is hidden. Pirinen (2006) estimated that one-third of all moisture and mould damage is hidden. The results of this study support the results and observations of those two earlier studies since about a quarter of the damage could not be detected from the surface of structures but required using destructive methods.

The moisture and mould damage of different structures were detected by very different methods as Table 3 indicates. This can probably be largely explained by the differences between structures. For example, a concrete slab with a moist soffit that is part of the base floor probably also has a moist top due to its capillarity, whereby its moistness can be detected by a surface moisture detector. On the other hand, the thermal insulation of a roof assembly is generally external to the air/vapour barrier which may prevent detecting damage from the surface of the structure. That may require, for instance, a mould sample from the thermal insulation of the roof assembly.

In the study 73.9 % of all damage was detected on the surface of structures (Detection methods I-III). Yet, it is important to note (Table 3) that only 39.9 % of the damage in roof assembly could be detected from the surface of structures. The share was highest at 82.5 % in walls in soil contact. Further study on detection methods suitable for different structures is needed.

The scope of the study was limited based on the hypothesis that if a building has no moisture and mould damage, related health symptoms and indoor air problems cannot occur there. Excessive repairs are not generally economically feasible, or even profitable. Thus, we should have criteria for the kinds of moisture and mould damage that should be repaired to avoid the occurrence of health symptoms. Repair of the smallest and slightest damage is not necessarily needed. Currently, we do not know what impurity-content level in relation to moisture and mould damage causes health symptoms for groups or individual users. This has been recognised earlier (Bornehag et al. 2001, 2004), but the research problem remains unsolved and further medical research is needed.

6 Conclusions

This study determined on the basis of moisture performance assessment reports on 76 buildings the methods used to detect moisture and mould damage in Finland. It also sought targets of development related to moisture performance assessments

petri.annila@tut.fi

based on these condition assessment reports and the practical experiences of researchers who have conducted moisture performance assessments.

According to the study, 73.9 % of moisture and mould damage can be detected on the surface of structures by sensory observations or surface moisture measurements. However, the share can be significantly smaller depending on the assessed structure: in roof assembly 39.9 % of the damage could be detected on the surface of a structure.

The study found that the mere time taken by a moisture performance assessment is long: the period between the completion of the assessment plan and the report was, on average, 183 days. Moisture and mould damage processes are long also in other respects and can take several years. All phases certainly have areas that can be improved so that the processes and the exposure of users to the impurities caused by moisture and mould damage can be shortened. The moisture performance assessment process also requires development.

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petri.annila@tut.fi

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petri.annila@tut.fi

PUBLICATION
II

Extent of moisture and mould damage in structures of public buildings

Annila, P. J., Hellemaa, M., Pakkala, T.A., Lahdensivu, J., Suonketo, J. and Pentti, M.

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Case study

Extent of moisture and mould damage in structures of public buildings

Petri J. Annila*, Matti Hellemaa, Toni A. Pakkala, Jukka Lahdensivu, Jommi Suonketo, Matti Pentti

Tampere University of Technology, P.O. Box 600, FI-33101 Tampere, Finland

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ABSTRACT

The study concentrated on the extent of moisture and mould damage in different structures in 25 public buildings in Finland. Users of all the buildings had health symptoms suspected to be the result of moisture and mould damage, which is why moisture performance assessments had been performed. The assessment reports on each building were available as research material. The reports indicated that the examined buildings suffered from multiple moisture and mould problems in several different structures. On average, however, a relatively small proportion of the total number of structures had suffered damage. On the basis of the research material, damage was most extensive in walls in soil contact (16.3%) and base floor structures (12.5%). The lowest damage rates were found in partition walls (2.4%), external walls (2.6%) and intermediate floors (2.5%). The results of the study underline the importance of thorough moisture performance assessments to ensure that all point-sized moisture and mould damage is detected.
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PUBLICATION III

Need to repair moisture- and mould damage in different structures in Finnish public buildings

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Need to repair moisture- and mould damage in different structures in finnish public buildings

Petri J. Annila*, Jukka Lahdensivu, Jommi Suonketo, Matti Pentti, Juha Vinha

Tampere University of Technology, P.O.B. 600, FI-33101 Tampere, Finland

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ABSTRACT

Moisture- and mould damage and resulting impurities are related to complex indoor air quality problems. This study focuses on the need to repair moisture- and mould damage in different structures. The research material consists of 168 Finnish public buildings. Based on research material, the highest need for repair is in timber-framed ground floor with crawl-in space, slab-on-ground structures, external walls in concrete-framed buildings and walls in contact with soil. A need to repair these structures exists in 56–85% of the examined buildings. The study reveals that buildings are multi-problematic: on average 3.1 main category structures were damaged in every studied building.

PUBLICATION IV

Reliablity of the detection of moisture and mould damage in visual inspections

Annila, P. J. and Lahdensivu, J.

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Reliability of the detection of moisture and mould damage in visual inspections

Petri J. Annila[1,*] *and Jukka Lahdensivu*[1]

[1]Tampere University, Faculty of Built Environment, Civil Engineering, Renovation and service life engineering of structures, Korkeakoulunkatu 5, FI-33720 Tampere, Finland

Abstract. Moisture and mould damage are common in Finnish public buildings. Due to the possible health hazards of such damage, more efficient detection methods and protocols are needed to examine it. The aim of this study is to examine the reliability of visual inspection in the detection of moisture and mould damage. The study points out that the reliability of all the research material is 70%. The highest reliability values concentrate on those structures where the repair need is highest. However, the range of reliability values is wide: from 0% to 100% depending on the age of building or structure. Reliability is highest in the most simplified structures and lowest in structures consisting of multiple layers of different building materials.

1 Introduction

Different types of visual condition inspection and walk-through inspections are widely used research methods, when moisture and mould damage, and indoor air quality or health issues are the main topics of scientific studies [e.g. 1-5]. However, these studies do not estimate the reliability of the research method used versus thorough condition assessments, which include openings in structures and more specific samplings and measurements. Pirinen [6] estimated that 1/3 of moisture and mould damage is hidden inside structures, so this damage cannot be detected by visual inspections. Pirinen [6] concentrates on small houses in Finland. Haverinen-shaughnessy et al., [7] have assessed the reliability of different building investigation methods, but clear recommendations on how to perform condition inspection have not been made.

The main research questions of this study are to determine the reliability of visual inspection versus thorough moisture performance assessments. The study focuses on Finnish moisture- and mould-damaged public buildings.

2 Inspecting the condition of buildings

Condition assessments and different condition investigations are the most commonly used methods for inspecting the condition and repair needs of buildings in Finland. Condition inspections are visual walk-through inspections mainly focusing on the repair need and normal ageing of structures, materials and HVAC and electrical systems. They result in estimates of the remaining service life and future repair needs. These inspections do not include, for example, the dismantling of structures, material samples or specific measurements. Recommendations and instructions have been given in Finnish national guidelines KH 90-00535 [8] and RT 18-11086 [9]. It is recommended that the condition inspection is repeated at intervals of 5-10 years.

Thorough condition investigations or assessments are much more accurate investigations than visual inspections. These investigations are usually carried out when it is probable that there are some problems or repair needs in buildings. If these problems are connected to moisture and mould damage, the investigation is called moisture performance assessment or building moisture and indoor air quality assessment. These assessments include, for example, the opening of structures, material sampling and measurements, especially different moisture measurements. Recommendations for the assessment are described in greater detail in national guideline [10]. The aim of the assessment is to identify all damage and to present repair recommendations.

Along with assessments and investigations, risk analyses are also used. These may focus on, for example, moisture or indoor air quality risks.

Condition inspections and moisture performance assessments have not prevented moisture and mould damage or indoor air quality problems, so professionals have discussed new routine inspections or methods of checking, which aim to detect critical factors causing such indoor air or moisture issues. The aim is also to eliminate such factors in order to prevent health issues and problems more efficiently in future.

Senate Properties, a company collaborating with the Finnish government in work environment issues and a

* Corresponding author: petri.annila@tuni.fi

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major property owner in Finland, has developed a model in which professionals go through a checklist [11]. From the perspective of structures, this checklist includes 20 topics. These topics are drying structures, control of rain- and surface waters, foundations, ground floors, load-bearing frame and walls, intermediate and uppermost floors, staircases and lifts, external walls and facades, windows and sills, external doors, balconies and terraces, eaves, roof coverings, skylight windows and other apertures, surface materials, sanitary rooms, fixtures, fireplaces and chimneys, and indoor air quality. All these topics are ranked from 1 to 5. Grade 1 means that immediately actions are needed. These actions could be more specific condition investigations or direct repair actions. Grade 5 means that the structure is like new.

The Senate Properties model has been tested in about 100 buildings. The model has proven to be an efficient and operative method for gathering data from numerous buildings and using this data to form a situational picture [12]. However, previous studies have pointed out [e.g. 1-5] that moisture and mould damage can be detected with the naked eye in many cases, so presumably the use of this kind of model not only detects moisture and mould damage, but also other indoor air problems and risks connected to them.

It is critical to evaluate the reliability of the model, something that has not yet been done. Even though the model identifies numerous issues in need of repair, it does not guarantee that the building will be safe and healthy for its occupants. There may be, for example, hidden damage or other indoor air pollutants, the detection of which requires more precise research methods than visual inspection.

3 Research material and methods

The research material consists of 168 public buildings where thorough moisture performance assessments have been performed. This study focuses only on moisture and mould damage in different structures when other indoor air quality problems and impurities are out of scope. Data relating to detection methods of moisture and mould damage has been collected from assessment reports in the moisture and mould damage database. The same database has also been used for analysis in previous studies [13-15] from other perspectives.

Detection methods for moisture and mould damage are listed in Table 1. If one of the following criteria is met in the examined structures, the structure is determined to be damaged. All five detection methods were used in thorough moisture performance assessments. The early detection of moisture and mould damage is done by visual inspection performed by a professional using methods I, II and III as presented in the table. It should be noted that method I includes only clear damage; moisture marks or unclear spots are not counted. In reality, these signs of moisture or mould damage are of course reasons for more closer inspections.

Table 1. Detection methods for moisture and mould damage.

Detection method	Definition	Included in thorough moisture performance assessment	Included in visual inspection
I	Mould damage, visible to the naked eye without magnification.	x	x
II	Unrepaired, active water leakage detrimental to the structure or building material that it wets.	x	x
III	A structure of building material found to be moist, extremely moist or wet by a surface moisture detector based on a five-step assessment scale: dry, a little moist, moist, extremely moist and wet.	x	x
IV	Relative humidity of the structure exceeds 80% in a drill-hole measurement.	x	
V	A material sample shows active microbial (fungal or bacterial) growth. The fungal and bacterial colonies are determined by dilution plating on MEA (2% malt extract agar) agar, DG18 (dischloran 18% glycerol agar) or TYG (tryptone glucose yeast) agar.	x	

3.1 Reliability of visual inspection

The main object of the research is to analyse the reliability of visual inspection versus thorough moisture performance assessments. The moisture and mould damage database include a total of 2,079 separate cases of moisture and mould damage. The detection methods used in each case are listed in the database. If method I, II, III or a combination of these have been used, the damage has been detected in visual inspection and thus detected early.

Every building and every structure were analysed separately, but not every case of damage. An example is shown in Figure 1. Two different cases of moisture- or mould damage were detected in a thorough moisture performance assessment. One of these (marked with '+' in Figure 1) was also detected by visual inspection, whilst the other (marked with '-' in Figure 1) was not detected by visual inspection using methods I, II or III. The reliability of visual inspection in this example is 100%, because at least one case of damage in the external walls was detected.

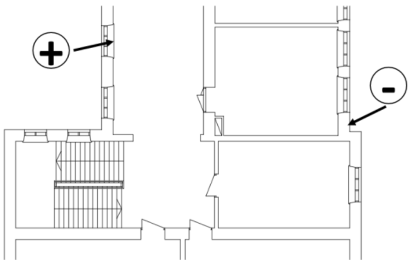

Fig. 1. Damage to the structure is detected if at least one case of damage is detected in a visual inspection. In this example, damage marked with the symbol '+' is detected, but detecting the other damage (marked with the symbol '-') through moisture performance assessment is needed.

It is considered that detecting all moisture and mould damage in a visual inspection is not necessary. The most critical thing is to identify those buildings that need more specific investigation like thorough moisture performance assessment or repair actions. The aim of actual condition investigation or assessment is to identify all different kinds of damage.

In the database, the buildings are divided into six different age groups. The structures are further sub-divided into 14 different subcategories. The age groups are A) 'before 1950', B) 1950-1959, C) 1960-1969, D) 1970-1979, E) 1980-1989 and F) 'after 1990. The structures are divided into subcategories 1) ridge roof, 2) flat roof, 3) slab-on-ground, 4) wooden ground floor with crawl space, 5) concrete ground floor with crawl space, external walls in 6) concrete, 7) timber framing, 8) log, 9) masonry- or 10) mixed frame building, 11) wall in soil contact, 12) concrete intermediate floor, 13) wooden intermediate floor and 14) partition wall. A similar classification was also used in a previous study [15].

4 Results

The research material consists of 168 public buildings. Moisture and mould damage was not detected in five buildings in thorough moisture performance assessments, equating to 3.0% of the examined buildings. In 12 buildings (7.1%), moisture and mould damage was detected in thorough moisture performance assessments, but not in visual inspection in a single structure. In the rest of the buildings (151, 89.9%) at least one of damaged structure was detected in visual inspection.

Table 2. Reliability of early detection in different structures and age groups. All values are percentages [%].

	roof		external walls					intermediate floors				ground floor with crawl space	
	ridge roof	flat roof	wall in soil contact	concrete building	masonry building	timber framing building	log building	concrete	timber	partition wall	slab-on-ground	concrete	timber
Before 1950	91		82		50		83	63	67	75	92		55
1950-1959	62		80	67	83			82		76	78	50	
1960-1969	33	50	83	46		33		100		86	88	80	
1970-1979	33	55	60	47		75		92		67	96	100	
1980-1989	80	100	14	45	0	55		67		77	88	75	
After 1989	0			100				100		100	83		
Totally	68	56	70	50	68	57	86	84	60	78	88	80	65

The reliability of early detection throughout the research material is 70%, which means that 30% of damage was not detected in visual inspection and is so-called hidden damage. Table 2 shows the reliability in different subcategories. The table presents only those categories containing five or more buildings: for example, the research material did not include enough flat-roofs, built before the 1960s. However, the row 'totally' includes all buildings from research material, also those age groups where the number of buildings is below five.

The reliability of visual inspection is highest in slab-on-ground structures (on average 88% of all damage was detected in visual inspection), external walls in log buildings (86%) and concrete intermediate floors (84%). The lowest reliability values were in the external walls of concrete buildings (50%), flat roofs (56%) and external walls of timber-framed buildings (57%). However, on average more than half the damage in these structures was detected in visual inspection. The reliability of visual inspection is, however, as low as 0% in some structures in certain age groups as shown in Table 2.

Figure 2 shows the reliability of visual inspection in those cases where more than five cases of damage were detected in the same age group and structure. The reliability is on average 73.7% and it seems that, when the number of cases of damage rises, so does the reliability of early detection. The higher the number of detections, the lower the effect on individual detections and buildings.

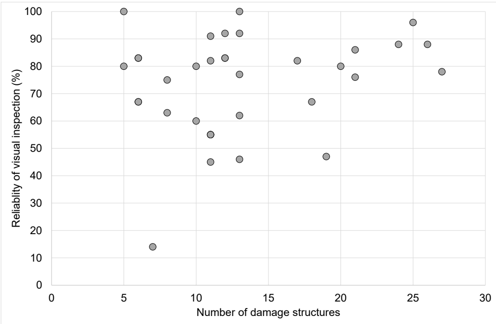

Fig. 2. Reliability of visual inspection, and moisture and mould damage repair need.

4.1. Correlation between reliability of visual inspection and repair need

The correlation between early detection and moisture and mould damage repair need is presented in Figure 3. The correlation coefficient is 0.244 over the entire research material. The highest reliability values (reliability over 90%) were obtained irrespective of repair need. The lowest reliability values (reliability below 40%) are concentrated in those structures where the repair need is lowest (below 50%). The presented repair need of structures is based on the author's previous study [15].

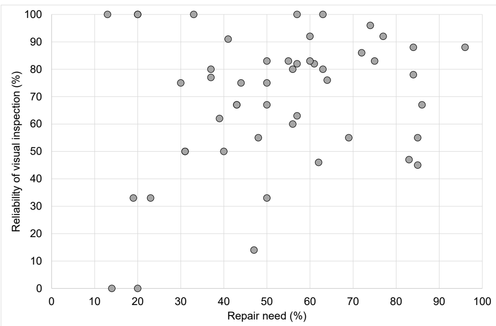

Fig. 3. Correlation between repair need and reliability of visual inspection.

The correlation coefficient may be a competent indicator when differences between structures and age groups are being studied. However, the amount of data in these subcategories is too low for this kind of analysis. Figures 4-13 shows the correlation between the reliability of early detection and the repair need for moisture and mould damage. External walls in log buildings, wooden intermediate floors and wooden ground floors are not presented due to the scarcity of data. The repair needs of these structures are 50%, 43% and 85%, respectively, and the reliability of visual inspection 83%, 67% and 55%, respectively as shown in Table 2.

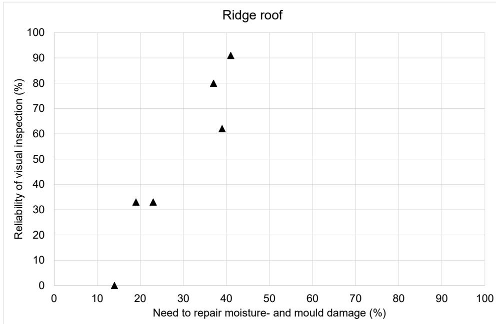

Fig 4. Correlation between repair need and reliability of visual inspection.

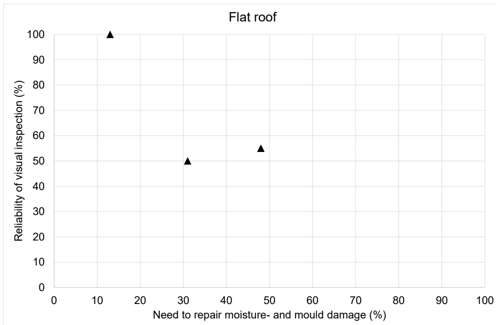

Fig. 5. Correlation between repair need and reliability of visual inspection.

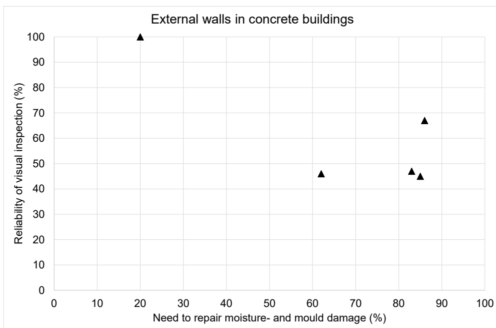

Fig. 6. Correlation between repair need and reliability of visual inspection.

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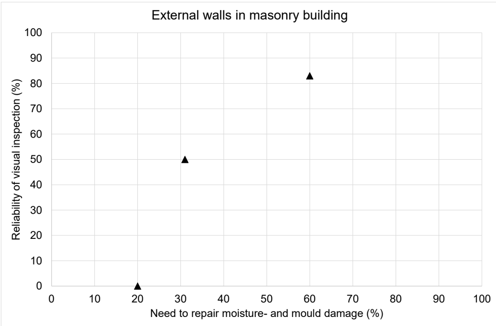

Fig. 7. Correlation between repair need and reliability of visual inspection.

Fig. 8. Correlation between repair need and reliability of visual inspection.

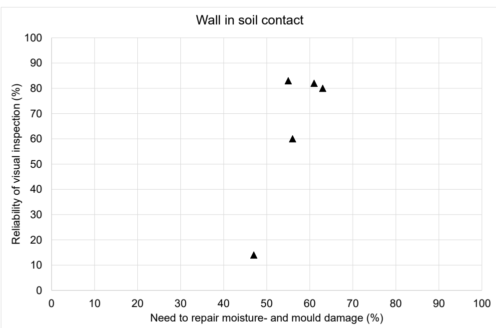

Fig. 9. Correlation between repair need and reliability of visual inspection.

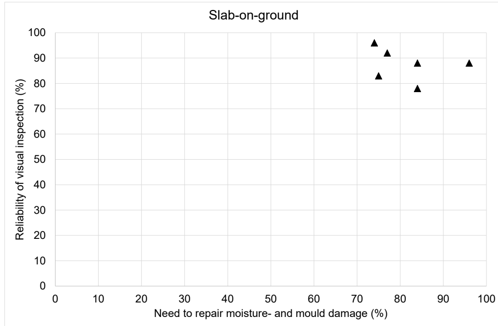

Fig. 10. Correlation between repair need and reliability of visual inspection.

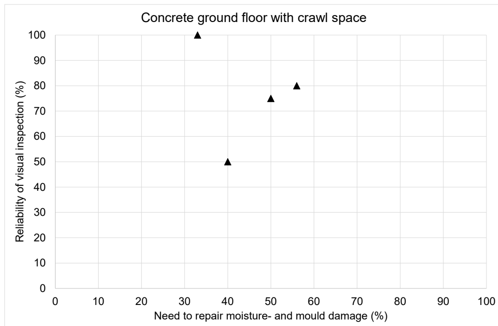

Fig. 11. Correlation between repair need and reliability of visual inspection.

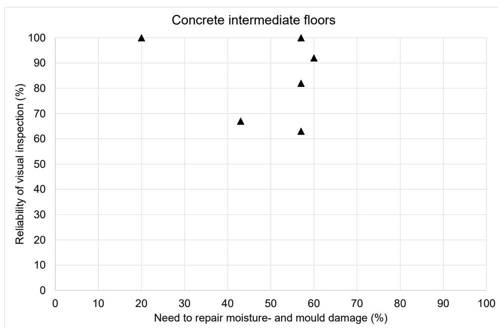

Fig. 12. Correlation between repair need and reliability of visual inspection.

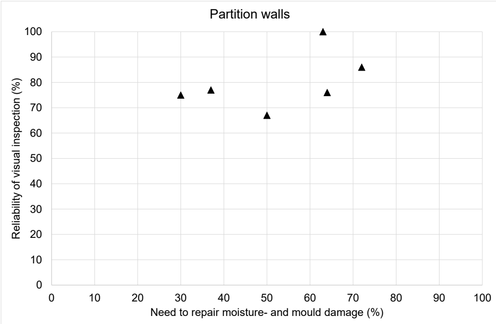

Fig. 13. Correlation between repair need and reliability of visual inspection.

5 Discussion

The reliability of early detection is highest in the most simplified structures as shown in Table 1. Log buildings, concrete intermediates floors built after the 1960s and slab-on-ground structures could be counted in this category in Finnish public buildings. These simplified structures consist of their main material and coatings when observed from inside the building. The most sensitive building material is usually located near the inner surface of structure, so the condition of the material and structure can be examined without dismantling the structure. The capillarity of these structures is usually high, which also moves moisture to the surfaces of the structures.

The reliability of early detection is lowest in the most complicated structures as shown in Table 1. Timber-based structures (ground floors with crawl space, external walls, intermediate floors, flat roofs) and external walls in concrete buildings could be counted in this category in Finnish public buildings. These structures consist of multiple layers of different materials and the most sensitive building material may be located inside the structure, so damage to that material cannot be detected without dismantling the structure.

These findings highlight the need to open these structures and sample the material in a thorough moisture performance assessment, as a visual examination could not detect problems or damage.

On average, the reliability of visual inspection is over 50% in every structure and 70% in total. It is therefore clear that, if walk-through inspections are used, they will highlight numerous cases of moisture and mould damage or the need for more precise condition inspections like moisture performance assessments.

When the correlation between the repair need of structures [15] and the reliability of visual inspection is compared (see Figure 3), it is important for reliability to be high when the repair need is high. None of the Figure 3 dots are located in the section of greatest risk: the low reliability of visual inspection (below 30%) and high repair need of moisture and mould damage (more than 50%).

Some dots in Figure 2 are located in the area where the reliability of visual inspection and repair needs are low. In certain buildings, such hidden damage may result in indoor air quality problems, but in the building stock as a whole these are not so remarkable. The lowest reliability values are from the external walls of masonry buildings and ridge roofs. As could be noted from Figure 3 and 6, the reliability of visual inspection in these structures rises as the repair need rises. The correlation coefficient of these structures is 0.95 and 0.93, respectively.

The tested model of Senate Properties [11, 12] has shown that walkthrough inspections detect moisture and mould damage and other risks connected to indoor air quality. However, the reliability of this model has not yet been studied, so it is unclear whether these findings will prevent indoor air quality problems in future. Moreover, there is a risk that the use of this kind of model will lead to a situation where property owners focus only on a few major issues, and hidden damage and its influence on indoor air quality are not considered. According to previous studies [e.g. 6, 7], some moisture and mould damage is hidden and cannot be detected without dismantling structures. In sum, walkthrough inspections are no substitute for thorough moisture performance assessments.

Lappalainen et al. [1] have pointed out that walk-through assessments can be used to determine the relative importance of repairs in moisture- and mould-damaged buildings. The results of this study are similar to previous studies [1, 11, 12]: walk-through inspections are useful tools to determine the condition and repair needs of multiple buildings, but major repair measures should still be based on thorough moisture performance assessments.

This study focuses only on buildings with problems, so it is unclear what the reliability of visual inspection would be if also used in the reference buildings. The tests of the Senate Properties model [12] have also concentrated on buildings where numerous problems and findings have been expected. It seems that property owners in Finland fear that studies using these kinds of models may identify new and as yet unknown problems connected to indoor air quality. These new findings could result in unexpected costs for property owners, so this fear may be a reason why buildings without indoor air quality problems are not included in the studies. It has not therefore been possible to carry out random sampling of the condition of the entire building stock. The condition of reference buildings or genuine random sampling should be included in some future studies.

The research material consists of thorough moisture performance assessments. It is probable that not every visual observation is mentioned in reports. This applies especially to those situations in which the condition investigator has carried out more precise measurements such as the dismantling of structures, material sampling or moisture measurements. Knowing all visual observations would probably improve the reliability of visual inspections.

The building stock includes many so-called risk structures in Finland. These are structures where moisture and mould damage are common, and in many cases, damage is hidden and severe. The greatest reason

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for damage is usually the poor thermal and moisture behaviour of structures under current moisture stresses. The risks of these structures are identified afterwards, so the structures are no longer used. The risk structures of buildings were outside the scope of this study but knowing them would improve the detection of hidden damage and especially the need for further condition inspection.

6 Conclusion

The total reliability of the visual inspection of moisture and mould damage is on a good level: 70% of moisture and mould damage can be detected in visual walk-though inspections, which includes surface moisture measurements. Reliability is highest in the most simplified structures and lowest in structures consisting of multiple layers of different materials. Timber-based structures (ground floors with crawl space, external walls, intermediate floors and flat roofs) and external walls in concrete buildings are structures where the reliability of visual inspection is lowest: 65%, 57%, 60%, 56% and 50%, respectively. Reliability is highest in the most simplified structures such as slab-on-ground (88%), external walls in log buildings (86%) and concrete ground floors with crawl space (80%).

The findings of the study indicate that walk-through inspections could be used to determine the condition of multiple buildings, but more precise moisture performance assessments are still needed when it is a question of multilayer structures and the repair of a whole building.

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