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Building envelope performance assessments in harsh climates: Methods for geographically dependent design

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Thesis for the degree of
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Innovation and Creativity

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Dissertation submitted for the Philosophiae Doctor Degree (PhD) in
Civil and Transport Engineering at the Faculty of Engineering Science
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Finally, a special thanks to my co-authors, and to my supervisors and management team; professor Jan Vincent Thue and professor Tore Kvande.

May 2006

Kim Robert Lisø

Summary

The lifetime of the built environment depends strongly on the severity of local climatic conditions. A well-functioning and reliable infrastructure is a precondition for economic growth and social development. The climate and topography of Norway puts great demands on the design and localization of buildings. The relationship between materials, structures and climatic impact is highly complex; illustrating the need for new and improved methods for vulnerability assessment of building envelope performance in relation to externally imposed climatic strains. Historically, major variations in climatic impact have led to corresponding large variations in building practice throughout the country - often well suited to local conditions. Today it is fair to say that sound building traditions and practice to some extent are being rejected in the quest for cost-effective solutions. Furthermore, projected changes in climatic conditions due to global warming will enhance the vulnerability within the built environment.

The primary objectives of the present dissertation are to increase the knowledge about possible impacts of climate change on building envelope performance, and to analyse and update methods for the planning and design of external envelopes in relation to climatic impact. This is accomplished through the development of integrated approaches and improved methods for assessing impacts of external climatic parameters on building envelopes, combining knowledge on materials, structures and relevant climate data, applicable for both historical data and scenarios for climate change. The results will contribute to more accurate building physics design guidelines, promoting high-performance building envelopes in harsh climates.

Approaches to assessments of the risks associated with climate change and buildings are suggested, identifying main areas of vulnerability in the construction industry. It is shown that there are benefits to be gained from the introduction of risk management strategies within a greater extent of the construction industry. A way of analysing the building economics of climate change is also proposed

Analyses of building defects are necessary in order to further develop tools, solutions and preventive measures ensuring high-performance building envelopes. To illuminate the vulnerability of different building envelope elements under varying climatic exposure, a comprehensive analysis of empirical data gathered from process induced building defect assignments is carried out. The amount of building defects in Norway clearly illustrates that it is not only the extreme weather events that need to be studied as a foundation for adaptation towards a changing climate. Furthermore, the analyses of defects reveal a fundamental need for climate differentiated design guidelines.

New and improved methods for geographically dependent design of building envelopes are proposed:

- A method for assessing the relative potential of frost decay or frost damage of porous, mineral building materials exposed to a given climate is developed.

- A national map of the potential for decay in wood structures is developed. Detailed scenarios for climate change for selected locations in Norway are used to provide an indication of the possible future development of decay rates.

- A method for assessing driving rain exposures based on multi-year records of synoptic observations of present weather, wind speed and direction is also presented.

These climate indices can be used as a tool for evaluation of changes in performance requirements or decay rates due to climate change under global warming incorporating data from regional- and local-level climate change scenarios. Historical records of climate data have finally been used to illuminate challenges arising when introducing international standards at the national level, without considering the need for adjustments to reflect varying local climatic conditions.

At present, building standards and design guidelines presuppose use of historic weather data. Historically, location-specific climate data have only to a very limited extent been applied systematically for design purposes, life cycle assessments, and climate differentiation of the suitability of a given technical solution in a given climate. The work is a first step towards methods and approaches allowing for geographically dependent climate considerations to be made in the development of design guidelines for high-performance building envelopes, and also approaches to assess the risks associated with the future performance of building envelopes due to climate change.

The dissertation focuses on methods for assessing impacts of external climatic parameters on a local scale, but with the use of daily and monthly averages of climate data. The reliability of climate indices or climate differentiated design guidelines is strongly dependent on the geographical spreading of the observing station network. The Norwegian network is not optimally distributed to fully embrace local variations, but provides a solid platform for the development of methods for geographically dependent design and guidelines on the appropriateness of different solutions in different climates.

Climate indices (using geographic information systems technology) allowing for quantitative assessment of building envelope performance or decay potential may be an important element in the development of adaptation measures to meet the future risks of climate change in different parts of the world. Finally, the work offers a conceptual point of departure for the development of a vintage model of the robustness of the Norwegian building stock.

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II. **Lisø**. K.R., Time, B., Kvande, T. and Førland, E. J. (2003) Building enclosure performance in a more severe climate, *Research in Building Physics – Proceedings of the 2nd International Conference on Building Physics* (Carmeliet J. *et al.* eds.), A.A. Balkema Publishers, Lisse, 309-317.

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XII. Meløysund, V., **Lisø**, K.R., Hygen, H.O., Høiseth, K.V and Leira, B. (2006) Effects of wind exposure on roof snow loads. *Building and Environment* (accepted).

These papers will be referred to by their Roman numerals.

1 Introduction

"We are venturing into the unknown with climate, and its associated impacts could be quite disruptive" (Karl and Trenberth, 2003, p. 1719)

1.1 Principal objectives and scope

The principal objectives of the present work are to increase the knowledge about possible impacts of climate change on building envelope performance, and to analyse and update methods for the planning and design of building envelopes in relation to external climatic impact. This is done through the development of approaches and methods for assessing impacts of external climatic parameters, combining knowledge on materials, structures and relevant climate data, applicable for both historical data and regional scenarios for climate change. The results are intended to contribute to more accurate building physics design guidelines and Codes of Practice, promoting reliable and high-performance building envelopes in harsh climates.

The work is a first step towards methods and approaches allowing for geographically dependent climate considerations to be made in the development of design guidelines for high-performance building envelopes, and also approaches to assess the risks associated with the future performance of building envelopes due to climate change. The close interrelation between the two is to be clearly illustrated.

1.2 The climate of Norway

The climate of Norway is extremely varied, the rugged topography being one of the main reasons for large local differences in temperatures, precipitation and wind velocities over short distances. The seasonal variations are also extreme. January is particularly eventful with frequent storms both in the mountains and along the coast. February is statistically a much friendlier month. However, the greatest temperature difference ever registered within a single month is from this month (location: Tynset, Hedmark County, -43.5ºC on February 8 1985, +10.9ºC on February 26, i.e. a temperature difference equal to 54.4ºC at the same station within the same month). August is the month with most registrations of nights where the air temperature does not fall below 20ºC, while September is one of the months with fewest extreme weather events. October often represents a distinct transition in weather conditions, with autumn storms along the coast of northern Norway and with the first snowfall in the eastern parts of the country. The two last months of the year are statistically also rather dramatic when it comes to both wind actions and all forms of precipitation.

The country's long coastline and steep topography make it particularly likely to experience extreme events like coastal storms, avalanches and landslides. From its southernmost point (Lindesnes, see Figure 1) to its northernmost (North Cape) there is a span of 13 degrees of latitude, or the same as from Lindesnes to the Mediterranean Sea. There are also large variations in received solar energy during the year. The largest differences are found in Northern Norway, having midnight sun in the summer months and no sunshine at all during winter.

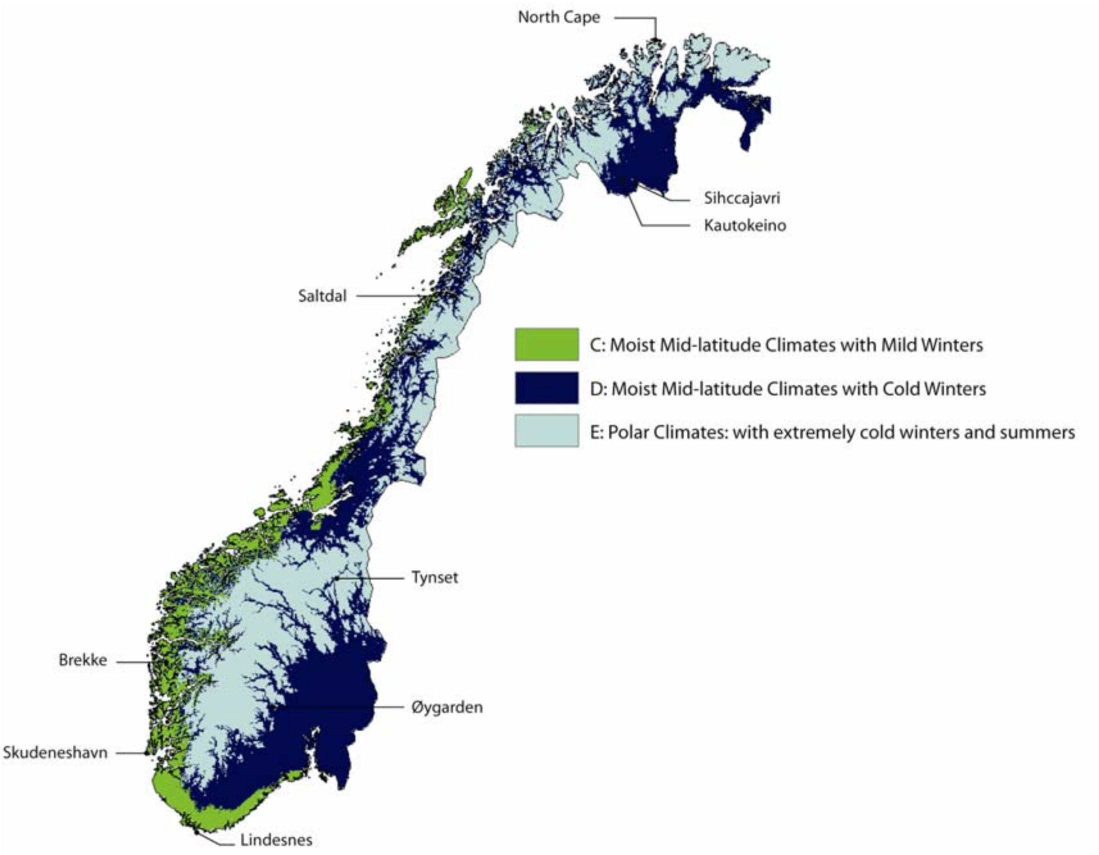

Figure 1. The climate of Norway based on the Köppen Climate Classification System (developed by Wladimir Peter Köppen around 1900, with several later modifications). The map is prepared by the Norwegian Meteorological Institute (www.met.no), using weather data (annual and monthly averages of temperature and precipitation) from the reference 30-year period 1961–1990. Locations referred to in Section 1.2 are marked on the map.

Norway has a much friendlier climate than the latitude indicates, thanks to its westerly location on the east side of a vast ocean, with a huge, warm and steady ocean current near its shores and a dominating southwesterly air flow from the Atlantic Ocean. The highest annual temperatures can be found in the coastal areas of the southern and western part of the country. Skudeneshavn (Rogaland County) on the southwest coast has an annual normal temperature of 7.7°C. In 1994, Lindesnes lighthouse (Vest-Agder County) recorded the highest annual temperature ever, with 9.4°C.

The coldest area throughout the year is the Finnmark Plateau (when excluding uninhabited mountain areas). One of the stations there, Sihccajavri, has an annual normal temperature of -3.1°C. The coldest year ever was in 1893, when Kautokeino (Finnmark County) recorded an annual temperature of -5.1°C. Sihccajavri equalled this in 1985. In the mountains, large areas have an annual temperature of -4°C or less. See Figure 1 for an illustration of the Norwegian climate according to the Köppen climate classification system. Moist mid-latitude climates with mild winters (group C) have a coldest month average between -3ºC and 18°C. Moist mid-latitude climates with cold winters (group D) have an average temperature above 10°C in their warmest months, and a coldest month average below -3°C. Polar climates (group E) are characterized by average temperatures below 10°C in all twelve months of the year. Most of the country has a moist mid-latitude climate with cold winters. The extensive coastline does for a large part sort under climate C, while Svalbard (not on the map), parts of Finnmark County and the mountain areas have a polar climate.

There are also large differences in the normal annual precipitation in Norway. The largest normal annual precipitation is found some miles from the coast of Western Norway. These amounts are also among the highest in Europe. Brekke in Sogn og Fjordane County has an annual normal precipitation of 3575 mm, and several other stations in this area follow close behind. Brekke has also the record for one-year precipitation, with 5596 mm in 1990. The inner part of Østlandet, the Finnmark Plateau, and some smaller areas near the Swedish border, are all lee areas in relation to the large weather systems mainly coming from the west. Common for these areas is the low annual precipitation and that showery precipitation during summer is the largest contributor. Øygarden at Skjåk (Oppland County, located less than 150 km in overhead line from Brekke) has the lowest annual normal precipitation with 278 mm. This is lower than the normal monthly precipitation for the 6 wettest months of Brekke. However, the lowest recorded precipitation for one year is only 118 mm, measured at Saltdal (Nordland County) in 1996.

The climate statistics in this section are obtained from www.met.no.

1.3 Climate data and the weather observation network

Climate is usually defined as the long-term average condition of the atmosphere at a geographical locality, including the normal and extreme deviation from this average condition. The climate, or "average weather", can be described in different ways. The most common way is to define "normal" periods (averages over e.g. the classical 30-year period, as defined by the World Meteorological Organization (WMO)), and to compare today's weather and observations with these reference periods. Weather observations in Norway have not historically been recorded as hourly averages, and even today this is done at only at a few stations at the largest airports in the country. Observations are typically done only a maximum of three times a day. There are about 550 observing stations in the country with manual recordings of precipitation, and about 150 observing stations for synoptic observations of climate variables such as temperature, air humidity, wind, atmospheric pressure, clouds and snow depth. Automated weather stations are becoming increasingly common, and there are now about 20 automated stations recording hourly temperature, wind and precipitation amounts.

Synoptic observations from most weather stations in Norway include the 10-minute average wind speed and direction at the time of observation as well as a numerical code identifying the state of the weather at the time of the observation. The objective is to provide the weather situation at a given point of time for a larger geographical area. Observations are done four times daily (2400, 0600, 1200 and 1800 UTC (Coordinated Universal Time)) at the larger stations and three times daily (0600, 1200 and 1800 UTC) at the more rural stations (i.e. these latter stations do not have midnight observations). Electronic records of synoptic observations go back to at least 1957 for most stations, the data being stored in the Norwegian Meteorological Institute's Climate archive (see www.met.no).

Historically, location-specific climate data have only to a very limited extent been applied systematically for climate differentiation of the suitability of a given technical solution in a given climate. Hourly climate data necessary for full numerical modelling of the performance of building envelope elements are only available for a handful of locations in Norway. The presented dissertation focuses on methods for assessing impacts of external climatic parameters on a local scale, but with the use of daily and monthly averages of climate data. The reliability of climate indices or climate differentiated design guidelines is strongly dependent on the geographical spreading of the observing station network. The Norwegian network is not optimally distributed to fully embrace local variations, but provides a solid platform for the development of methods for geographically dependent design and guidelines on the appropriateness of different solutions in different climates.

1.4 Climate change

The Intergovernmental Panel on Climate Change (IPCC) defines climate change as "a statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period (typically decades or longer). Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use" (Houghton *et al.*, 2001). The United Nations Framework Convention on Climate Change (UNFCCC), in its Article 1, defines climate change as: "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods".

Modern climate change is now dominated by human influences large enough to exceed the bounds of natural variability, the main source of global climate change being human-induced changes in atmospheric composition (Karl and Trenberth, 2003). According to Crowley (2000) "a 21st-century global warming projection far exceeds the natural variability of the past 1000 years, and is greater than the best estimate of global temperature change for the last interglacial". Man induced climate change can be avoided in the long term only by reducing global emissions of greenhouse gases to a small fraction of present levels within one or two centuries (Hasselmann *et al.*, 2003). Regional changes in climate, particularly increases in temperature, have already affected several physical and biological systems in many parts of the world, for example shrinkage of glaciers, thawing of permafrost and lengthening of mid- to high-latitude growing seasons ((McCarthy *et al.*, 2001). Measures aimed at halting global climate change through greenhouse gas mitigation options need to overcome many technical, economic, political, cultural, social, behavioural and/or institutional barriers which prevent the full exploitation of the technical, economic and social opportunities of these mitigation options (Metz *et al.*, 2001).

Global warming will lead to changes in the local climate in Norway in this century. Climate scenarios for Norway emanating from the project “Regional climate development under global warming” (RegClim) suggest changes in mean and extreme values of temperature, precipitation and wind. The most realistic scenarios for changes in global climate are based on Atmosphere-Ocean General Circulation Models, AOGCM’s (Houghton *et al.*, 2001). These global climate models are “fully coupled, mathematical, computer-based models of the physics, chemistry and biology of the atmosphere, land surface, oceans and cryosphere and their interaction with each other and with the sun and other influences like e.g. volcanic eruptions” (Karl and Trenberth, 2003). The spatial resolution in the recent AOGCMs is still too coarse to enable these global climate models to reproduce the climate on regional or local scale. To deduce detailed scenarios for future climate development in different parts of Norway, both dynamic and empirical downscaling techniques are being applied on integrations with global climate models. The downscaled scenarios indicate a general increase in temperature and precipitation rates across the country (see e.g. *Paper II*; Benestad, 2005). Consistent with emerging global patterns, the projected temperature increases are at a maximum during the winter and at a minimum during the summer and warming rates increase from south to north and from coast to inland. Precipitation scenarios suggest increased precipitation in existing wet areas and periods, in agreement with scenarios at the global scale. Extreme amounts of precipitation will appear more often in all of Norway. The RegClim scenarios also suggest a moderate increase in wind in the southernmost areas and along the coast of Central Norway, with most of the increase manifesting itself during the autumn and winter months.

The climate is a product of both ordered forcing and chaotic behaviour (Rind, 1999). Several sources of uncertainties exist related to both scenarios for global climate change, and to the effects of global warming on regional-level climate. The regional scenarios should not be considered as forecasts in an absolute sense. They offer insights into the likely range and nature of future weather scenarios. The regional scenarios for climate change are continuously being improved, increasing their reliability along with knowledge on uncertainties connected with inaccurate climate models, random climate variations and different downscaling techniques.

The possible effects of climate change, and the subject of risk management, adaptation and mitigation, are now being addressed in several parts of the world. Challenges confronting the built environment in responding to the potential impacts of climate change were one of the main themes in a special issue of Building Research & Information in 2003 (*Paper I*; Sanders and Phillipson, 2003; Shimoda, 2003; Larsson, 2003; du Plessis *et al.*, 2003; Mills, 2003; Hertin *et al.*, 2003; Steemers, 2003).

The amount of building defects in Norway (see Section 1.5) clearly illustrates that it is not only the extreme weather events that need to be studied as a foundation for long-term adaptation towards a changing climate. A well-functioning and reliable infrastructure is an important basis for economic growth and social development.

Norway, one of the wealthiest countries in the world, is normally considered to be resilient to the impacts of climate change, but vulnerability varies considerably across scale (O'Brien *et al.*, 2004). The lifetime of buildings and other infrastructure depends on the harshness of local weather conditions. The regional scenarios developed by climate scientists for climate change as a result of global warming must therefore be used as a basis for studies of the possible technological, economic and social impacts of such change.

1.5 Climate adaptation and building defects

The historical development of the Norwegian building stock and building traditions implies both an adaptation towards different preconditions for use of buildings and varying styles of architecture, but also an adjustment towards the extreme climatic variations throughout the country. Changes in building practice also reflect the economic development and new trends and requirements in standard of living. Wood is, due to easy access, the most common building material.

As of January 2006 a total of 3,722,012 buildings are registered in Norway. 1,413,516 of these are residential buildings, and there 2,308,482 non-residential buildings (see Table 1 in *Paper V* for a distribution of residential buildings by building type and County). Today approximately eight out of ten people live in urban areas compared to 50 per cent after World War II. Figure 2 provides a population density distribution for the country. In Norway as a whole there are more than 900 urban settlements (a collection of houses is described as an urban settlement if at least 200 people live there and the distance between houses is less than 50 metres). Compared to other European countries, Norwegians more often live in detached houses or other small dwelling houses, which they own. While eight out of ten Norwegian households live in houses that they own, this applies to only four out of ten German households (source: Statistics Norway, www.ssb.no).

Natural disasters caused by extreme weather events are one of the major challenges confronting the built environment. However, the amount of building defects not covered by natural disaster insurance is also tremendous. Investigations carried out by SINTEF Building and Infrastructure indicates that the cost of repairing process induced building defects in Norway amounts to 5% of the annual capital invested in new buildings. Correcting faults and repairing defects in buildings during the construction process is estimated to cost roughly the same amount as repairing buildings in use, e.g. another 5% (Ingvaldsen, 1994). With an annual investment in refurbishment and new construction of 16.5 billion euro (as in 2003), it is reasonable to estimate that approximately 1.65 billion euro is being spent on repairing defects or damage to buildings every year (provided that Ingvaldsens 1994-estimate is still valid). Defects related to the building envelope constitute 66% of the process induced building defects investigated by the institute in the 10-year period 1993-2002 (*Paper V*). A bulk of the defects (76%) is related to moisture as the main source causing defects. This experience-based knowledge provides valuable insight on the vulnerability of the building stock, as it shed light on the underlying causes of defects and enables assessment of preventive actions.

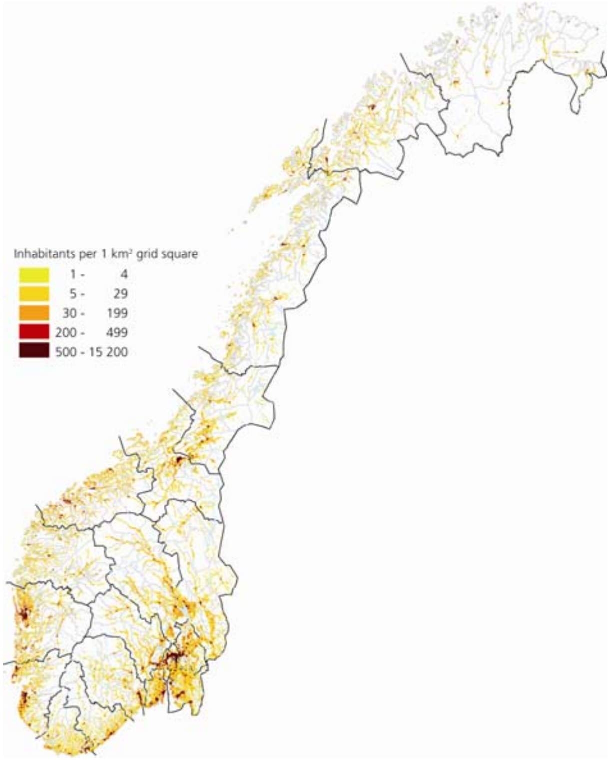

Figure 2. Population density in Norway (as of January 1 2002). From Statistics Norway, www.ssb.no.

The increasing demands in the construction industry for profit and shorter construction periods, combined with extremely varied climatic impacts during the construction process, also prove to be a difficult circle to square. The increasing number of extreme weather events reminds us of how vulnerable society is when faced with major climatic variations and severe weather. Projected changes in climatic conditions due to global warming will further enhance vulnerability within the construction industry.

The most influential government regulatory measure to ensure adherence to building codes and standards is the Technical Regulations under the Norwegian Planning and Building Act (PBA), which since 1997 have been performance-based. The principal motive for a transition from a prescriptive-based code to a performance-based code in Norway has been to stimulate to an increase in the quality of buildings and a reduction of the amount of building defects. The transition has been a gradual process, and the performance-based way of thinking was introduced in Norwegian building regulations as early as 1969 (Norwegian Building Research Institute, 2003). The former Norwegian Building Research Institute (now part of SINTEF) had developed a basis for performance requirements for different building technology solutions. The institute were advocating the necessity of first defining the function of different building structures and elements, and then determine the performance requirements in accordance with the functional demands they were to fulfil. The following example illustrates the distinction between prescriptive-based codes and performance-based codes: Prescriptive codes or guidelines declare how e.g. a wall is designed and constructed, but do not define the performance in use. Performance-based codes and guidelines, on the other hand, do define the performance requirements for the wall to fulfil, but do not specify which physical solution to be chosen. The first managing director of the institute, Øyvind Birkeland (1910-2004), won international recognition for his efforts in the development of performance-based requirements as a foundation for building codes.

Preliminary findings from a case study of process induced building defects suggest that the adoption of a performance-based building code has indeed led to a positive change in quality (Mehus *et al.*, 2005). However, even if the amended PBA appears to be contributing towards improved quality of construction, defects, flaws, and premature damage are still flourishing in new construction. Furthermore, design of details crucial to durability and service life of buildings is often omitted or they are improvised on site (Stenstad *et al.,* 2005).

The transition from a prescriptive to a performance-based code has strengthened the demand for supporting standards and design guidelines. The Building Research Design Sheets in the SINTEF Building Research Series comply with the performance-based requirements in the building code, and are an important reference to “pre-accepted” solutions in the technical regulations. The principal objective of the design sheets is to adapt experience and results from practice and research in such a way that they can be of practical benefit to the construction industry. The main purpose is to provide guidelines, solutions and recommendations that encourage high quality in the planning, design and construction of buildings. The series consists of 816 design sheets, the first sheets being published in 1958. It is the most used planning and design tool amongst Norwegian architects and engineers and is found on nearly all construction sites. The design sheets are continuously being updated to comply with the building code and experience-based knowledge.

An analysis of climate differentiated design recommendations in the Building Research Series and technical approvals issued by SINTEF Building and Infrastructure illustrates the challenge at hand (Almås, 2005). The analysis clearly reveals the need for suitable time-series of climate data for the development of climate indices allowing for geographically dependent building envelope design guidelines. All 816 Building Research Design Sheets and the 241 Technical Approvals issued by the institute at the time of investigation were examined.

In a great many incidents it is necessary to advise against the use of a given technical solution or material combination, simply because the local climate conditions are too harsh for the particular solution to obtain its expected lifetime or to harsh to avoid defects within a reasonable level of reliability. Evidently, rough qualitative descriptions of the climate, such as “wind exposed areas”, “cold areas”, “harsh climates”, “areas with high driving rain impact” or “exposed areas along the coast” are not appropriate as a foundation for climate adaptation with a necessary level of reliability. Instead, limit values with respect to the climatic loads that have to be taken account of must be clarified and expressed as a function of climate properties and material- or performance properties, together with national maps of climate zones for different purposes (see e.g. Figure 3). Such approaches to climate adaptation could to a large degree “replace” vanishing local craftsmanship knowledge on climatic conditions.

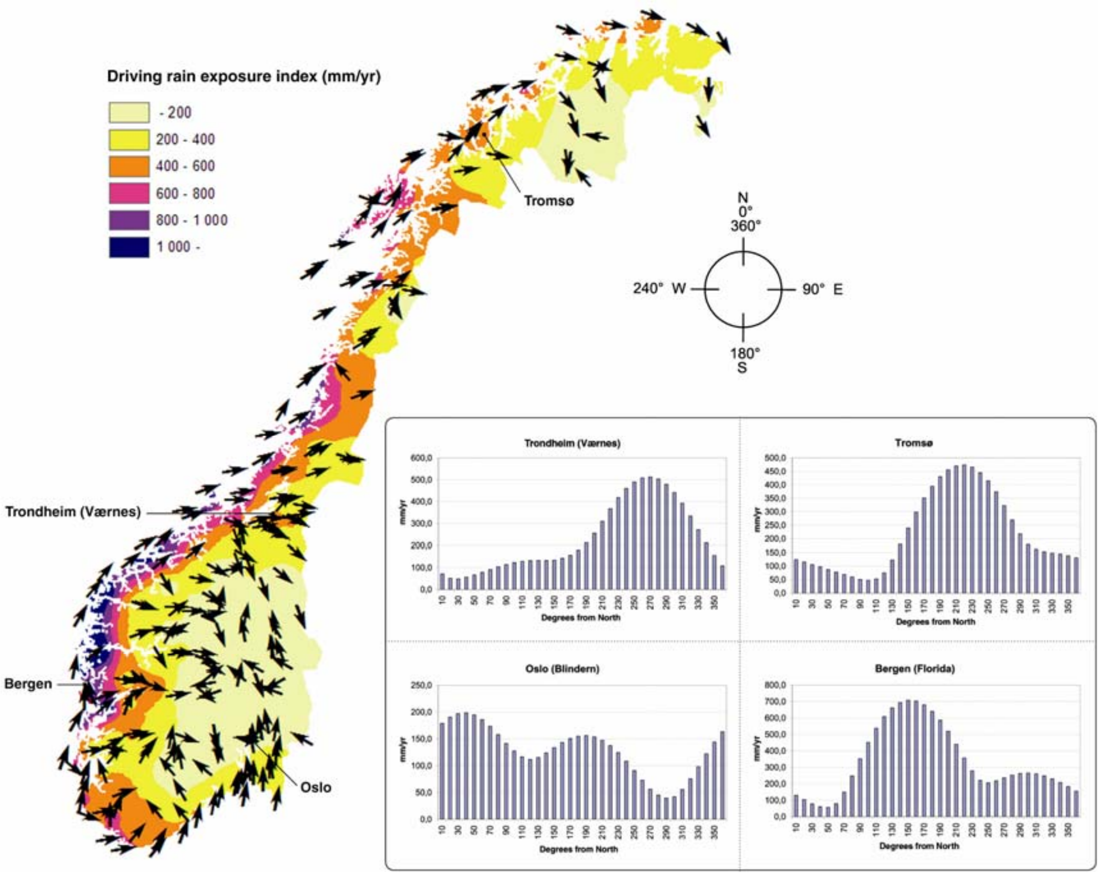

Figure 3. Driving rain map for Norway (for the normal period 1961-1990). The map presents annual driving rain amounts (illustrated with colour scale) from the main wind direction (indicated with arrows) that gives the highest driving rain amounts at each observing station. The map provides driving rain exposure on the wall in mm/yr. Driving rain amounts are shown for every 10-degree sector for the cities of Oslo, Bergen, Trondheim and Tromsø. Topographic effects are not considered in the development of the map, some locations may therefore be more or less protected than the map expresses. The map is developed in cooperation with the Norwegian Meteorological institute, according to the new method given in *Paper XI*.

The technical solutions presented in the Building Research Series are in general meant to have a reliability level suitable for all parts of the country. Standard technical solutions for all types of climate are in some cases appropriate (e.g. weather-protective flashings, see *Paper VI*). But, in most cases, climate differentiated performance requirements and solutions provide the highest level of reliability. This realization constitutes the starting point for the presented work.

Climate data are also important in measurements and simulations of the energy performance of buildings. A main challenge for the construction industry is the following up of the Directive on the Energy Performance of Buildings (EPBD) (2002/91/EC). The Directive introduces a more holistic view on the energy performance of buildings, and a mandatory energy performance certificate for all buildings being constructed, sold or rented out. The construction industry has to be actively involved in the implementation of the Directive to meet the overall goal of promoting the improvement of energy performance. More efficient use of energy in the built environment is essential to reach political goals within Norway and the

European Union on reliable energy supply and emissions of greenhouse gases. The built environment affects nature through energy use, emissions and use of raw materials. The construction of buildings, for instance, account for about 40% of all energy use in the country, and operation of buildings account for about 50% of all electricity use, and the consumption is rising (NOU, 1998). The long lifetime of buildings implies that choices made today when constructing new buildings and renovating existing buildings, will have fundamental impact on the long-term energy use in the society.

Today, the term climate adapted buildings and building structures is the common designation given to structures which are planned, designed and performed to withstand various types of external climatic impact – including precipitation, snow deposition, wind, temperature and exposure to the sun. The “robustness” of the Norwegian building stock, including the development of methods for classifying different climatic parameters and their impact on building envelope performance can be assessed through analysis of statistical data, historical trends in the design and construction of buildings and built environments, and practical experience related to past building defects and damage. There are, however, very few, if any, easily accessible design guidelines or methods for assessing geographically dependent climatic exposures related to external moisture loads (one of the main sources causing defects in buildings).

2 Main findings

2.1 Introduction

The dissertation is divided into three mutually dependent main parts (part A-C). Each part consists of four papers (see *List of papers*).

Approaches to assessments of the risks associated with climate change and building envelope performance are presented in Part A, identifying main areas of vulnerability in the construction industry. Norwegian climate policy is briefly reviewed and the predicted climatic changes over the next decades are described. Climate vulnerability is explained, and possible adaptation policies are suggested (*Paper I*). This is followed by an overall view of building physics related challenges concerning the design of building envelopes, together with a few detailed climate change scenarios for Norway (*Paper I* and *Paper II*). A way of analysing the building economics of climate change is also proposed (*Paper III*). The model describes important aspects to be considered and identifies stakeholders, and the paper discusses interdependencies between potential implications of climate change and the behaviour of building owners. Finally, ways of using modern risk management theories as a basis for the development of strategies to meet the challenges of future climate change is presented. It is shown that there are benefits to be gained from the introduction of risk management strategies within a greater extent of the construction industry (*Paper IV*).

An overall review of the robustness of the Norwegian building stock is presented in part B, focusing in particular on analyses of empirical data from process induced building defect assignments as a point of departure for climate impact differentiation assessments. Analyses of building defects are essential in order to further develop tools and solutions ensuring high-performance building envelopes. To illuminate the vulnerability of building envelopes under varying climatic exposure, a comprehensive analysis of building defects is carried out (*Paper V*). The overall analysis presented in *Paper V* is supported by two case studies on building defects (*Paper VI* and *Paper VII*). The case of flashing (*Paper VI*), a central part of all building envelopes, is chosen to illustrate that parts of the building envelope are particularly vulnerable to defects, and thus justifying a higher level of robustness than other parts of the envelope. Simplified flashing solutions could be acceptable in some areas, but it is an inexpensive insurance to choose flashing solutions with a higher climatic level of reliability. A comprehensive review of process induced building defect assignments related to masonry shows that the performance of masonry depends on climatic exposure at the very local level. The case of masonry structures (*Paper VII*) clearly reveals the fundamental need for climate differentiated design guidelines and recommendations. Finally, results from a field investigation of structural safety in different vintages of buildings compared with current regulatory requirements are presented in *Paper VIII*.

Part C presents methods for geographically dependent design of building envelopes. A method for assessing the relative potential of frost decay or frost damage of mineral materials exposed to a given climate is expressed in *Paper IX*. A national map of the potential for decay in wood structures in Norway is presented in *Paper X*. Detailed scenarios for climate change for selected locations in Norway are used to provide an indication of the possible future development of decay rates. A method for assessing driving rain exposures based on multi-year records of synoptic observations of present weather, wind speed and direction is presented in *Paper XI*. These and other indices, with established quantified relations between climatic impact and material behaviour or building performance, can be used as a tool for evaluation of changes in performance requirements or decay rates due to climate change under global warming incorporating data from regional- and local-level climate change scenarios as indicated in *Paper X*. Historical records of climate data have also been used to illuminate challenges arising when introducing international standards at the national level, without considering the need for adjustments to reflect local climatic conditions. The appropriateness of the exposure coefficient given in the design standard on roof snow loads now in force is analysed (*Paper XII*), illustrating the importance of scale in standardisation. Norway has areas with both high snow loads and high frequencies of wind. It is shown that the exposure coefficient does not reflect the actual effects of wind exposure on roof snow loads in these areas.

An overview of main findings is presented in the following sections, referring to the twelve individual papers constituting this dissertation. Detailed presentations of results are given in the individual papers.

2.2 Methodology overview

The following research methods have been applied to obtain the presented results:

- Analyses of climate change scenarios (*Paper I*, *Paper II* and *Paper X*).
- Overall analyses of data from the Ground Property, Address and Building Register (GAB register) as a basis for a vintage model of the robustness of the Norwegian building stock (*Paper III* and *Paper VIII*).
- Analyses of risk assessment methods (*Paper IV*).
- Analyses of building defect assignment reports in the SINTEF Building and Infrastructure’s Building defects archive (*Paper V*).
- Case studies of building defect assignment reports related to weather-protective flashings and masonry structures (*Paper VI* and *Paper VII*).
- Field investigations of snow loads and wind actions on buildings (*Paper VIII*).
- Analyses of climate data from the Norwegian Meteorological Institute’s Climate archive (*Papers IX-XII*).
- Literature surveys (all papers).

Methods and delimitations are thoroughly described in the referred individual papers.

2.3 Part A: Approaches to performance assessments under a changing climate

Preparing for climate change impacts (Paper I)

Global warming is going to lead to changes in the local climate in Norway, and there are a large number of areas that need to be targeted in order to reduce the sensitivity of the built environment and thus vulnerability to climate change. Measures aimed at adjustments in the built environment, such as alterations of government regulatory measures, building standards and design guidelines, constitute only a partial adaptation to climate change. In order for adaptation to be effective and realizable, larger societal adjustments are needed. This is here demonstrated through examining climate change adaptation in Norway, focusing specifically on the built environment. Climate change could have a major impact on both the everyday weather and the frequency of extreme weather events. The safety levels in building regulations and codes with regard to undesirable incidents should therefore be reviewed regularly in order to uphold a proper level of reliability. A related challenge, demonstrated by e.g. the damages of the hurricane that hit Northwest Norway in 1992, is the inability to ensure that building codes are adhered to in practice. Ways to strengthen institutional capacity to implement appropriate building standards and Codes of Practice is an important element in adaptation to climate change (addressed in particular in *Paper IV*). It is probable that climate change will adversely affect property insurance. Insurance companies could be rendered vulnerable to climate change through changes in the frequency of storms and floods throughout the country.

The harsh and varied climate means it is particularly important to take into account climatic challenges at the local level. Both the functionality of the existing built environment and the design of future buildings are likely to be altered by climate change impacts. The construction industry’s determination and ability to respond to climate change will be an important factor in the development of adaptation strategies.

Building envelope performance in harsh climates (Paper II)

Climatic impact from precipitation, wind, temperature and exposure to the sun causes extensive degradation and damage to the built environment every year. The understanding of how degradation and damage can best be reduced is of significant importance in the design and construction of buildings. Building materials, structures and external envelopes will in the future probably have to withstand even greater climatic impact in parts of Norway than today. The weather trend in Norway over the last 10–15 years, with mild autumn-winter seasons with heavy precipitation and frequent storms along the coast, is expected to intensify.

The work provides an overall view of building physics related challenges concerning the design of roofs and façades, together with a few detailed climate change scenarios for Norway. Climate change will have different climatic impacts on different types of buildings depending on scale, use, design, construction and location, as discussed in *Paper II*.

The building economics of climate change (Paper III)

A way of analysing the building economics of climate change is proposed based on two approaches. Firstly it is the putty-clay approach to the theory of investment and production. The starting-point for this approach is that the scope for choosing different designs of a building is far broader before than after the building is erected. I.e. a building consists of elements that are costly to change once the building is erected, and of elements that are more easily maintained. The other pillar is the real options approach. This approach highlights the fact that information relevant for decision makers arrives over time. Immediate decisions should take into account that they affect possible future actions and their profitability. I.e. immediate decisions affect the value of real options.

The potential benefits or adverse implications of climate change on the building stock can be addressed at different levels:

- How will the performance and cost of operating of existing buildings be affected, if the buildings characteristics are kept unaltered?
- How should existing buildings be adapted to changes in climatic impact? At what costs can this be done, and when should it be done?
- How will the technical and economic lifetime of buildings be influenced?
- How will the choice of technology, materials and design in new construction be affected?
- How will the time path of the level of new construction be affected?

The analytical framework developed in *Paper III* is intended to be applicable at all these levels. The existing building stock will be less suitable than new buildings, under a new climate regime. Nevertheless, for the larger part of the building stock it will be profitable to continue the use. The economic lifetime of existing buildings will in part depend on their adaptability to changed climate conditions. Given the long lifetime of the building stock, the time before the whole building stock is optimally adapted to a new climate regime can amount to a hundred years or more.

The building stock some time into the future consists of the building stock of today and of future new construction. Parts of the present building stock will in the future be adapted to externally imposed changes in the environment, while parts are kept as is. Analysis of how the building stock is affected by climate change should handle this diversity. This diversity should be treated within the framework of some kind of vintage model. Formulation of such a vintage model involves complex problems of aggregation. A central tool in this aggregation will be considerations of how the use value of different parts (or classes or vintages) of the existing building stock are expected to evolve over time as more reliable climate models are developed.

The model describes important aspects of the building economics of climate change, and identifies stakeholders. It is a model of the decisions of a building owner facing an uncertain evolvement of the climate. The model shows that the decisions are affected by both the expected profitability of the different actions, and on the effects the actions have on the profitability of future choices. Hence, using a real option approach enhances the understanding of actions taken by owners of buildings. Some simple results are derived. Climate change can reduce both conversion activities (e.g.

reconstruction or refurbishing) and the occurrence of scrapping of buildings. Hence, future climate uncertainty can in fact increase the economic lifetime of a building.

Integrated approach to risk management of climate change impacts (Paper IV)

Building standards, Codes of Practice, design guidelines and operational procedures are today based on historic weather data. The existing building stock is in the next decades likely to be exposed to significantly different climatic strains than they are today, due to climate change. This work discusses the use of modern risk management theories as a basis for the development of cross-disciplinary strategies to meet the challenges of future climate change within the built environment. First, climate vulnerability and adaptation is discussed in general. Next, a point of departure for the support of decision-making aimed at reducing climate vulnerability in the built environment is suggested, using established risk management strategies and Norway as starting point. Finally, possible ways of supporting decision-making aiming at ensuring sustainable buildings are suggested, applying a flexible combination of risk-based, precautionary and discursive risk management strategies.

There are large uncertainties associated with the future performance of the built environment due to changes in external climatic impact. In order to develop adaptation strategies, one must find effective ways of strengthening institutional capacity. Cross-disciplinary risk-based management strategies, together with design guidelines that accounts for both historical local climatic conditions and potential future changes, can be an important step towards a more active and dynamic way of ensuring a high-quality construction process and a sustainable built environment in the light of the unknown risks of future climate change.

For large, complex building projects there is an established tradition of using risk analysis methods. This tradition has not moved from large-scale to more “trivial” building. Obviously, there are benefits to be gained from the introduction of modern risk-based management strategies within a greater extent of the construction industry. Three different strategies (risk-based, precautionary and discursive strategies) are discussed. The choice of strategy is strongly dependent on the characteristics of the risk at hand. Facing the future risks of climate change, it is suggested that a flexible approach using a combination of these strategies can help reduce potential impacts. Reducing the potential for defects or damage through the development of technical and organizational preventive measures (a risk-based management strategy) while at the same time applying the precautionary principle and discursive strategies in the design, construction and geographical localization of buildings, is likely to increase the robustness of the built environment in light of the unknown risks of climate change.

For the described integrated approach to risk management of future climate change impacts to be successful, it is necessary to ensure careful co-operation along vertical decision-making lines: i.e. from government regulatory bodies via local regulatory bodies and inhabitants, research communities and company management to the craftsmen on site.

2.4 Part B: Review of the Norwegian building stock and building practice

Process induced building defects in Norway (Paper V)

Empirical data on building defects provides valuable information on the performance and robustness of buildings in different climates, and are necessary in order to further develop tools and solutions ensuring high-performance building envelopes. To better understand the vulnerability of building envelopes under varying climatic exposure, a comprehensive analysis of building defects is carried out. SINTEF Building and Infrastructure's archive of building defect assignments represents one of Norway's most important sources of knowledge on types of process induced building defects and related causes. This knowledge has now for the first time been systematically investigated. The building defects archive reveals serious deficiencies in the construction industry with regard to knowledge about correct design and construction of building envelopes.

Defects related to the building envelope constitute 66% of the investigated process induced building defect cases in the 10-year period 1993-2002 (2,423 cases registered and described in 2,003 assignment reports). Moisture as the main source causing the defect replies for as much as 76% of all investigated cases in the 10-year period. Approximately 20% of the building defects are reported within the first year, and about 48% of the defects are reported within 5 years after completion of the building.

Many types of building defect cases are classical and recurring problems, indicating a general lack of knowledge amongst the actors in the construction industry concerning fundamental principles of building physics in particular. The findings also support investigations concluding that the construction industry is not able to learn from past experience. The results finally throw light on the need for tools and measures allowing for geographically dependent climate considerations to be made in the planning, design and carrying out of building envelopes.

It is possible to substantially reduce the amount of building defects in Norway. To reach future national defined goals on building defect reduction it is crucial to be familiar with both the technical and process induced causes initiating defects or damage. A future national building defects archive, in which the here-described archive should be a central contribution, would be an important part of this work; as such an archive would shed light on the underlying causes of defects and enable assessment of preventive actions.

High-performance weather-protective flashings (Paper VI)

As a rule, building defects starts to develop shortly after completion of the building. Poor planning, design and carrying out of critical elements, with consequential moisture damage to underlying or adjacent structures are the direct or contributory cause of much of these defects. These findings are supported by this case study of building defect assignments associated with weather-protective flashing, a central part of all building envelopes. A total of 175 assignment reports on flashing defects from the period 1963-2001 are analysed.

The case study clearly shows that certain faults and deficiencies are recurring items. Windowsill/weatherboard flashings comprise as much as 41% of the building defect cases associated with weather-protective flashing. Defects related to parapet flashing comprise 27% of all cases included in this investigation. Complicated geometry makes great demands on flashing techniques. Very often the flashings are not seen as an integral part of the building envelope. With few exceptions, instances of defects are located in Norway's coastal areas. Existing flashing solutions in the Building Research Design Sheets have been further developed, based on the results from the analysis. Improved high-performance flashing solutions are presented for a number of typical problem areas. Finally, recommended best-practice flashing solutions for a number of typical problem areas are provided. The results are implemented in the Building Research Design Sheets, and also used as a basis for the carrying out of new field studies and laboratory investigations (the results will be available in due course). Despite the investigation having quantitative weaknesses, it must be considered as being an important qualitative step towards identifying problem areas.

The results calls for a redefinition and strengthening of existing performance requirements for weather-protective flashings in harsh climates, as a basis for the improvement of existing flashing design, guidelines and workmanship. Simplified flashing solutions could be acceptable in areas with low and moderate driving rain exposure. However, the economic benefit from such simplification is marginal. In light of a more severe climate in parts of the country due to the uncertain risks of future climate change, it would be a fairly inexpensive insurance to choose flashing solutions with a higher climatic safety level.

Climate adapted design of masonry structures (Paper VII)

Empirical data on the design and performance of masonry buildings in Norway is presented in *Paper VII*, based on a comprehensive analysis of 302 process induced building defect assignments related to masonry in the 20-year period 1983-2002. Masonry structures are normally considered "maintenance-free" if properly designed and constructed, and when located in relatively dry climates with low driving rain exposure. However, methods and solutions for a typical sheltered inland climate are not necessarily appropriate in a more exposed climate. It is therefore of utmost importance to establish the most significant challenges concerning design of masonry structures under different climate conditions in order to identify research and education needs. Analyses of building defects should form part of approaches aimed at revealing these challenges. Data on building defects are necessary in order to further develop high-performance masonry structures, but scientific studies of masonry defects are almost absent in international journals today. The results presented are a first approach towards improved European design guidelines for climate adapted masonry structures.

In the Scandinavian countries wood are the most common building material, and also the most common cladding material for domestic buildings in Norway – due to easy access to wood. External walls below ground level have, for domestic buildings, traditionally been carried out in LECA masonry (Light Expanded Clay Aggregate), particularly widespread in the period 1960-1990. There are few masonry houses in Norway older than 200-250 years. Most of them are to be found in cities like Oslo, Bergen, Trondheim, Kristiansand, Stavanger and Ålesund. There are also rather few masonry buildings in the three northernmost counties of Norway. Nevertheless, masonry has a long-established and natural place in Norwegian building traditions. When correctly designed and constructed, and with due consideration paid to the distinctive features of masonry, few other materials can match its durability characteristics. However, the level of learning amongst the different actors in the construction industry involved in the design and performance of masonry structures varies greatly. The review also shows that the performance of masonry depends on climatic exposure at the very local level.

Moisture related masonry defects (80% of the investigated cases) clearly dominate the picture in Norway, largely due to a lack of both understanding and attention in the carrying out of masonry buildings. Driving rain and frost action are the principal climatic challenges to be considered in the pursuit of high-performance masonry structures in harsh climates. Shrinkage and thermal expansion or contraction, the most frequent defect category in this investigation, dominates independent of the climatic impact. It is a defect category more dependent on the design and construction of masonry structures.

The investigation also discloses the fact that merely small errors or mistakes can bring about major and often irreparable defects or damage to masonry structures. A large part of the investigated cases could have been avoided through more detailed engineering and applied knowledge on existing design guidelines. The investigation finally reveals the need for guidelines to ensure local climate adaptation, and improved design guidelines and recommendations on movement joints.

Reliability of the existing building stock (Paper VIII)

A field investigation have been performed to obtain a reliable indicator as to whether existing buildings in Norway meet current regulatory requirements concerning safety against collapse owing to snow loads and/or wind actions, and also to establish a basis for analyses of future climate change impacts on the Norwegian building stock. The analyses include design documentation studies and field investigations of 20 existing buildings in five high-snowfall and five high-wind municipalities in Norway. Special attention has been paid to exposed types of buildings, and the buildings have been randomly selected within the exposed building categories.

The existing rules for determining wind loads (introduced in 2002) have led to most of the buildings investigated having greater calculated reliability against collapse owing to wind load than the current regulations require for new buildings. For buildings in municipalities exposed to wind, for tall buildings or in places with special topographical conditions, safety may, on the other hand, decrease. The rules for determining snow loads (introduced in 2001), however, have led to most of the buildings investigated having lower calculated reliability against collapse owing to snow loads than the regulations now requires.

Representative trends for the building types investigated have been found. 18 out of 20 buildings have a utilization ratio of more than 100%. The design requirements for 95% of the buildings have increased since they were built. Nevertheless, one would assume that the buildings had built-in reserve capacities resulting in fewer buildings experiencing a utilization ratio of more than 100%.

The investigation indicates too low reliability for a considerable number of buildings according to current regulations, when evaluating the possible consequences of the conclusions in a national perspective. Potentially 4.5% of the Norwegian building stock may have too low capacity according to current regulations. Design snow loads may have increased for 4.7% of the total bulk of buildings. Scenarios for future climate change indicate both increased winter precipitation and increased temperature, and will result in changes regarding snow loads on roofs in parts of the country. An increase in frequencies of strong winds in areas also exposed today is also estimated. According to these scenarios the future reliability of buildings in these areas could decrease.

2.5 Part C: Methods for climate adapted design

A frost decay index for porous, mineral building materials (Paper IX)

The development of design tools for the assessment of frost decay risk is important because freezing and thawing of porous, mineral materials in combination with large amounts of precipitation represent a significant challenge in the design and construction of climate adapted high-performance building envelopes. Frost resistance of brick, concrete and rendering mortar is tested according to internationally standardised methods. Test methods are given for different countries (dividing countries in far too coarse national-level climate zones), but there exists no classification of local- or regional level climate zones for frost durability assessment purposes.

The frost resistance of porous, mineral materials depends on a complex set of material properties and on the climatic impact on the material. A navigable way of ensuring local climate adapted high-performance building envelopes is found to be accomplished through the development of climate classifications or climate exposure indices for different building materials and building envelopes. A relative potential of frost decay or frost damage of mineral materials exposed to a given climate is in this work expressed as a simple index incorporating information about the number of freezing events and 4-day rainfall sums prior to freezing events for the different months of the year, based on multi-year records of daily air temperatures and rainfall data.

A possible objection to the method could be that the index does not include the effects of wind. The moistening of e.g. a façade material is of course dependent on geographic orientation and wind conditions. But, in the end, the relative potential of a climate to promote frost decay or frost damage is basically guided by the two climate parameters included, namely freezing events and rainfall. The results are based on long-term series of climate data that are readily available. Data from 168 weather stations in Norway are analysed, using weather data from the reference 30-

year period 1961-1990. The proposed climate index is to be justified in the future in relation with building defects observations in different climates.

Further development of the index will focus on providing quantitative information on the connection between climatic exposure in different regions and durability of different porous, mineral building materials. This work should also include analyses of the influence of frost period lengths on the assessment of frost damage risk mapping. Field investigations and laboratory testing of different materials are needed for validation and further improvement of the index. An important issue to be addressed is the connection between frost resistance and suction rate, especially of interest for clay bricks.

Decay potential in wood structures (Paper X)

Climate indices allowing for quantitative assessment of building envelope performance or decay potential may be an important element in the development of adaptation measures to meet the future risks of climate change. Established quantified relations between climatic impact and material behaviour or building envelope performance, can be used as a tool for evaluation of the need for changes in performance requirements or decay rates due to climate change under global warming incorporating data from regional- and local-level climate change scenarios. A national map of the potential for decay in wood structures in Norway, based on Scheffer’s climate index formula, represents an example of a first step towards such measures. Climate data from 115 observing stations for the reference 30-year period 1961-1990 is used. The climate index distribution allows for geographically differentiated guidelines on protective measures. Detailed scenarios for climate change for selected locations in Norway are used to provide an indication of the possible future development of decay rates. The scenario index values clearly points towards a pronounced increase in the potential for decay in wood structures at all locations. In general, climate change scenarios also indicate an increase in the average annual precipitation in Norway during the next 50 years, and thus strengthening this trend. The projected precipitation increase rates are generally smallest in southeastern Norway, and largest along the northwestern and western coast.

The quantitative connection between wood decay rates and climatic impact should be further investigated. Field- and laboratory investigations are needed to further improve the reliability of the index for Norwegian climate conditions, including measurements of decay rates in different climates and in different types of wood. Important issues to be considered are the low temperature limit for growth in wood decaying fungi in evidence in Norway, and appurtenant observed growth rates to temperature.

A driving rain exposure index for Norway (Paper XI)

Driving rain represents one of the greatest challenges in the design and construction of outer wall structures in Norway. There is, however, no practical tool available for assessing driving rain exposures in the planning and design of the built environment, and there has been little progress made during the past 50 years in the quantification and presentation of driving rain values at weather stations around the country, despite the fact that the nature and quantity of driving rain varies significantly.

Weather data at most observing stations in Norway are not recorded as hourly values and are therefore not suitable for existing standardised methods for the determination of driving rain exposure requiring hourly values of rainfall and mean directional wind speed. An alternative method for assessing driving rain exposures based on multi-year records of synoptic observations of present weather, wind speed and direction is therefore developed. Distributions of numbers of rain observations and wind speeds versus wind direction combined with average annual rainfall totals has yielded quantitative information about driving rain exposures at stations, providing a representative picture of the relative frequency of driving rain from different directions. A complete national driving rain map is presented in Figure 3.

The principal advantages with the presented method are that the angular distributions of driving rain loads obtained are high resolution in terms of wind direction and that the results are based on long-term series of climate data that are readily available. Where the 1955 driving rain map for Norway yielded driving rain intensities in only four principal directions (north, south, east and west), the new method, with 36 directions, gives a much more detailed picture of the directional dependence of wind-driven rain at a weather station. And, driving rain indices presented in this work are from 30 years of synoptic observations representing the most recent climate.

The method can also be used to evaluate changes in driving rain loads due to climate change under global warming, through the incorporation of data from climate change scenarios into the methodology.

Effects of wind exposure on roof snow loads (Paper XII)

International standards do not necessarily reflect national distinctive climate characteristics and topography features. The preparation of national appendices associated with various types of climatic impact is necessary in order for these characteristics to be considered. Again, local climate data needs to be analysed in order to evaluate the validity of proposed methods and tools for assessment and differentiation of climatic loads for various architectural or engineering purposes. In the Norwegian Standard NS 3491-3 “Design of structures – Design Actions – Part 3: Snow loads” from 2001 a new coefficient was introduced, making it possible to take into account the effect of wind exposure on roof snow load. The definition of this exposure coefficient is based on ISO 4355 “Bases for design of structures – Determination of snow loads on roofs”. It is defined as a function of the mean temperature in the coldest winter month and number of days with a wind velocity above 10 m/s. Three winter temperature categories and three winter wind categories are defined, resulting in 9 exposure coefficient values varying from 0.5 to 1.0

dependent on these categories. As an effect of the introduction of the coefficient the snow load on a sheltered roof becomes twice as large as the snow load on a windswept roof.

Norway is a mountainous country with main settlements in valleys and on the coast (see Figure 2). This basically results in two characteristic type of wind climate near settlements. Inland settlements experience a wind climate governed by valleys, resulting in main wind direction along the valley and a decrease in strength due to topographic effects. The coastal area suffers a higher frequency of extreme winds due to less topographic effects. During snowfall the presence of wind will make the snow load on the roof differ from the snow load on undisturbed ground. Redistribution may naturally also occur in periods without snowfall. Finally, the properties of snow are an important aspect to be considered when trying to assess redistribution of snow on a roof due to the effects of wind.

The investigation of the suitability of the proposed exposure coefficient reveals that the coefficient does not reflect the actual effects of wind exposure on roof snow loads in Norway. The main reasons for this can be attributed to oversimplifications in the definition of the coefficient, but also to the extremely varied climate of Norway. The country has areas with high snow loads and high frequency of wind, areas in which the exposure coefficient is expected to achieve its lowest value. These areas are however not pointed out as areas where wind blows snow away from roofs when using the definition as given in the standard. The definition is also based on oversimplifications of snow transport theories. It must be revised and improved to serve as an applicable tool for calculating design snow loads on roofs. These results clearly illustrate the need for methods allowing for climate differentiation in design guidelines for Norway. Further work will focus on developing a definition reflecting the physical processes more correctly, including the influence of the length of snow accumulation on the properties of the snow cover.

3 Concluding remarks

The presented work is a first step towards methods and approaches allowing for geographically dependent climate considerations to be made in the development of design guidelines for high-performance building envelopes, and also approaches to assess the risks associated with the future performance of building envelopes due to climate change. Approaches to risk assessments associated with the potential implications of climate change on building envelope performance are presented, identifying main areas of vulnerability. For large, complex building projects there is an established tradition of using risk analysis methods. It is shown that there are benefits to be gained from the introduction of risk management strategies also in small-scale building. A way of analysing the building economics of climate change is also proposed. The performed analyses of empirical data from process induced building defect assignments clearly illustrate the vulnerability of building envelopes under varying climatic exposure.

New and improved methods for geographically dependent design of building envelopes are proposed, enabling both historical weather data and scenarios for future climate change to be considered. A method for assessing the relative potential of frost decay or frost damage of porous, mineral building materials exposed to a given climate is presented, as well as a national map of the potential for decay in wood structures. Detailed scenarios for climate change for selected locations in Norway are in the latter method used to provide an indication of the possible future development of decay rates in wood structures. A method for assessing driving rain exposures based on multi-year records of present weather, wind speed and direction is also developed. These and other indices, with quantified relations between climatic impact and material behaviour or building performance, can be used as a very suitable tool for evaluation of changes in performance requirements or decay rates due to climate change under global warming incorporating data from regional- and local-level climate change scenarios. Historical records of climate data have also been used to illuminate challenges arising when introducing international standards at the national level, without considering the need for adjustments to reflect local climatic conditions. The work will also contribute to the pre-normative research for the continued development of Norwegian and international standards. This is particularly important with respect to the preparation of additional Norwegian appendices associated with the various types of climatic impact.

The ongoing establishment of an electronic building defects archive, initiated as part of this work, will be an important tool in both the continuous efforts towards higher quality in the construction industry and the development of strategies aiming at learning from experience. The archive will also be an important element in the continuous development of more accurate criteria and Codes of Practice regarding the design and functionality of critical elements of buildings in the Building Research Design Series. And, the building defects archive will be an important educational tool in the establishment of knowledge on building defects amongst academic institutions and different actors in the construction industry.

Finally, overall estimates on the robustness of the Norwegian building stock and the need for local climate considerations can be assessed through analyses of statistical data on the state of buildings, and systematic analyses of experience based building defects. The Ground Property, Address and Building Register (GAB Register) provide some information on the state of different vintages of buildings. Aggregated information on material combinations, technical solutions, design, craftsmanship and location would form an ideal starting point for a “vintage model” based on the data set in the GAB register (as indicated in *Paper III*). Valuable information can be drawn from the year of completion alone. A relevant description of localisation could determine the climatic impacts the buildings have been exposed to, using historic weather data and geographic information systems technology (GIS). To generate the suggested vintage model it is primarily required to describe the building stock along dimensions necessary to obtain reliable estimates on how building operating costs and defect occurrence are being affected by climatic strains. The necessary degree of detail along these dimensions must be clarified, together with assessments on the amount of data necessary for single buildings. There are large inconsistencies in the data set in the GAB register, but information on building types, year of construction and geographical localisation are readily available. The aggregation of data from these buildings is a matter of data handling to be considered in parallel with the development of a vintage model. The dissertation work offers a conceptual point of departure for the development of a vintage model of the robustness of the building stock. Historic trends in the design and construction of buildings and built environments are valuable sources of information in this context. Historic weather data and statistical data from insurance companies (natural damage) could serve as an enlarged basis for such a vintage model.

Building standards and design guidelines presuppose use of historic climate data. Location-specific climate data have only to a very limited extent been applied systematically for design purposes, life cycle assessments, and climate differentiation of the suitability of a given technical solution in a given climate. Projected changes in climatic conditions due to global warming will further enhance vulnerability within the construction industry and the built environment. GIS-based climate indices allowing for quantitative assessment of building envelope performance or decay potential may be a significant component in the development of risk mapping and adaptation measures to meet the future risks of climate change in different parts of the world.

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The master’s students have been supervised by K.R. Lisø and J.V. Thue

Individual papers

Part A
Approaches to performance assessments under a changing climate

I. **Lisø**, K.R., Aandahl, G., Eriksen, S. and Alfsen, K. H. (2003) Preparing for climate change impacts in Norway's built environment. *Building Research & Information* **31**(3/4), 200-209.

II. **Lisø**. K.R., Time, B., Kvande, T. and Førland, E. J. (2003) Building enclosure performance in a more severe climate, *Research in Building Physics – Proceedings of the 2nd International Conference on Building Physics* (Carmeliet J. *et al.* eds.), A.A. Balkema Publishers, Lisse, 309-317.

III. Nordvik, V. and **Lisø**, K.R. (2004) A primer on the building economics of climate change. *Construction Management and Economics* **22**, 765-775.

Viggo Nordvik and Kim Robert Lisø have developed the analytical framework presented in Paper III. Nordvik had main responsibility for the formal formulation and interpretation of the model. Lisø had main responsibility for the assessments concerning building performance and climate change, as a basis for the development of the microeconomic model. The paper is a joint work performed and written by Nordvik and Lisø.

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Preparing for climate change impacts in Norway's built environment

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This paper provides an overview of the Norwegian climate policy and of the practical implications of preparing Norway for climate change, with special emphasis on the challenges confronting the built environment. Although the Norwegian government has been relatively proactive in instituting measures aimed at halting global climate change, less attention has been paid to the challenge of adapting to climate change. The global climate system is likely to undergo changes, regardless of the implementation of abatement policies under the Kyoto Protocol or other regimes. The full range of impacts resulting from these changes is still uncertain; however, it is becoming increasingly clear that adaptation to climate change is necessary and inevitable within several sectors. The potential impacts of climate change in the built environment are now being addressed. Both the functionality of the existing built environment and the design of future buildings are likely to be altered by climate change impacts, and the expected implications of these new conditions are now investigated. However, measures aimed at adjustments within individual sectors, such as altering the criteria and codes of practice for the design and construction of buildings, constitute only a partial adaptation to climate change. In order to adapt effectively, larger societal and intersectoral adjustments are necessary.

Keywords: adaptation strategies, building performance, building stock, climate change, climate policy, global warming, risk, vulnerability, Norway

Cet article donne les grandes lignes de la politique climatique de la Norvège et des implications pratiques de la préparation de ce pays aux changements climatiques, l'accent étant mis sur les défis pour le cadre bâti. Bien que le gouvernement norvégien ait été relativement proactif dans l'institution de mesures qui visent à stopper ces changements, il se soucie moins du défi que constitue l'adaptation à ces changements. Il est vraisemblable que le système climatique global va connaître des changements quelles que soient les mesures de réduction mises en œuvre au titre du Protocole de Kyoto ou d'autres mécanismes. On ne connaît pas encore toutes les conséquences qu'auront les changements climatiques. Il devient toutefois de plus en plus certain qu'il faudra s'adapter à ces changements et que cette adaptation est inévitable dans plusieurs secteurs. Les auteurs s'intéressent ensuite aux conséquences potentielles des changements climatiques sur le cadre bâti. Il est probable que la fonctionnalité du cadre bâti existant et la conception des futurs bâtiments seront modifiées par les conséquences des changements climatiques. On analyse désormais les implications attendues de ces nouvelles conditions. Les mesures qui visent à des ajustements dans des secteurs donnés, comme la modification des critères et des Codes de pratique en matière de conception et de construction de bâtiments, ne constituent toutefois qu'une adaptation partielle aux changements climatiques. Pour une véritable adaptation, il faudra passer par des ajustements d'ordre sociétal et intersectoriel de plus grande ampleur.

Mots clés: changements climatiques, réchauffement global, performances des bâtiments, parc immobilier, vulnérabilité, stratégies d'adaptation, politique climatique, risque, Norvège

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Introduction

Empirical observations and modelling increasingly point to global warming and long-term changes in the climate system. The Intergovernmental Panel on Climate Change concludes that most of the warming observed over the last 50 years is attributable to human activities, and that anthropogenic climate change is likely to persist for many centuries. Adapting to the impacts of climate change thus represents a key challenge for researchers and policy-makers in the coming years (McCarthy *et al.*, 2001). Norway is exposed to a harsh climate and many facets of Norwegian society are, and will continue to be, affected by both climatic events and future climatic changes. The ability to respond to climatic change in terms of averting negative consequences and capitalising on any potential benefits arising from it is central to managing vulnerability in Norway. Adaptation here refers to the adjustments needed to take account of changing climate conditions in order to reduce vulnerability.

In this paper, it is argued that measures aimed at adjustments in individual sectors, such as alterations of technical regulations and building standards, constitute only a partial adaptation to climate change. In order for adaptation to be effective, however, larger societal and intersectoral adjustments are also necessary. This is demonstrated through examining climate change adaptation in Norway, focusing specifically on the built environment.

First, Norwegian climate policy is briefly reviewed and the envisaged climatic changes in Norway due to global warming over the next 50 years are described. Fifty years is, of course, a relatively short period in a climate change context. The main reason for focusing on the next 50 years is that detailed studies of regional climate change have been undertaken for this period. It should be recognised, however, that it appears likely that climate change will accelerate after 2050 with current trends in emission of greenhouse gases. This observation reinforces the main conclusions of the paper.

Next, climate vulnerability in the Norwegian context is explained, focusing in particular on the relationship between physical exposure, sensitivity, coping capacity and vulnerability, and the implications for approaches to adaptation. This is followed by an overview of the challenges concerning possible impacts of climate change on building performance to exemplify the sensitivity of a specific sector.

Finally, several possible adaptation policies are suggested for Norway in general, and for the construction industry specifically. We conclude that research and policy-making in Norway need to address sectoral issues as part of larger societal issues in order to foster the development of necessary adaptation strategies.

Norwegian climate policy

In response to the threat of global climate change, several government policy initiatives aimed at reducing greenhouse gas emissions in Norway have emerged. Following the politically 'charged' summer of 1988 and the Toronto declaration, and in the run up to the Rio conference in 1992, the Norwegian parliament established as a preliminary target that Norwegian CO_2 emissions be stabilised at their 1989 levels no later than 2000. As an initial step toward this target, a CO_2 tax was introduced in 1991 covering the majority (approximately 60%) of national emissions, including the large petroleum activity-related sources in the North Sea. Export-oriented and power-intensive industry emission sources were exempted from the tax. Although the tax rate was differentiated among sources, it was relatively high for the petroleum sector, the service sector and for individual households (approximately US$50 per ton of CO_2 emitted). The intention at the time of the introduction of the tax was to extend the scope and rate of the tax in tune with developments at the international level.

As it turned out, little if anything happened internationally. In light of this inaction, the national target was abolished a few years after its establishment. The original CO_2 tax structure was retained, however, mainly for revenue reasons.

A new initiative in Norwegian climate policy was taken following Norway's signing of the Kyoto Protocol in late 1997, when the government advanced a proposal to widen substantially the tax base of the CO_2 tax. However, this proposal was not approved by parliament, which instead called for the introduction of a national emission quota trading system (cap and trade). After first a green and then a white paper, successive governments eventually produced a proposal for the early introduction of a national emission quota trading regime for those sectors previously exempted from the CO_2 tax, while enforcing the existing CO_2 tax for the sectors already covered. Such a proposal would allow for a smooth linkage to an eventual internal European Union (EU) emissions trading system. The national trading system was approved by parliament in the summer of 2002 and it is expected to be operational as of 2005. Should the Kyoto Protocol enter into force, it is expected that a full quota trading system excluding the CO_2 tax will be operational from the beginning of the first commitment period in 2008.

A number of additional, but substantially smaller, measures have also been introduced in the Norwegian climate policy over the years. A tax on waste disposal is one such example. Most energy-efficiency measures are also presently classified as climate policy.

Although the government has been relatively proactive in instituting measures aimed at halting global climate change, comparatively little attention has been paid to the potential effects of climate change on Norway and on how to cope with and address these. The government white paper on climate (Ministry of the Environment, 2001), for example, does not discuss adaptation. A later addition to the white paper (Ministry of the Environment, 2002) indicates that while the government has a role in research, in disseminating information and in strengthening expertise, planning and developing measures are the responsibility of individual sectors and of regional and local authorities. At present, therefore, there is no conscious holistic adaptation policy at the national level.

Climate change in Norway

Climate change scenarios

Global warming is likely to lead to changes in the local climate in Norway. The impacts of local climate changes may necessitate adjustments and thus deserve policy attention. Climate scenarios for Norway emanating from the project 'Regional climate development under global warming (RegClim)' (www.nilu.no/regclim) (Figures 1 and 2) suggest changes in mean and extreme values of temperature, precipitation and wind. The scenarios are downscaled from a global climate model run by the Max-Planck Institute, assuming a 1% p.a. increase in CO_2 concentrations from 1990, estimating a near doubling in 2050. The downscaled scenarios indicate increasing temperatures across the country. Consistent with emerging global patterns, the projected temperature increases are at a maximum during the winter and at a minimum during the summer, and warming rates increase from south to north and from coast to inland. The mean winter temperature may increase by approximately 2°C in the northern areas of the country over the next 50 years. Generally, the stabilising influence of the ocean leads to the inland changes being greater than in the coastal areas. Precipitation scenarios for Norway conform to those at the global scale in that we see increased precipitation in existing wet areas and periods. Thus, in parts of Western Norway (including the Bergen region), the scenarios indicate that there will be an additional two days per year with daily precipitation exceeding 50 mm. The RegClim scenarios suggest a moderate increase in wind in the southernmost areas and along the coast of Central Norway, with most of the increase manifesting itself during the autumn and winter months. The mean winter temperature may increase by approximately 2°C in the northern areas

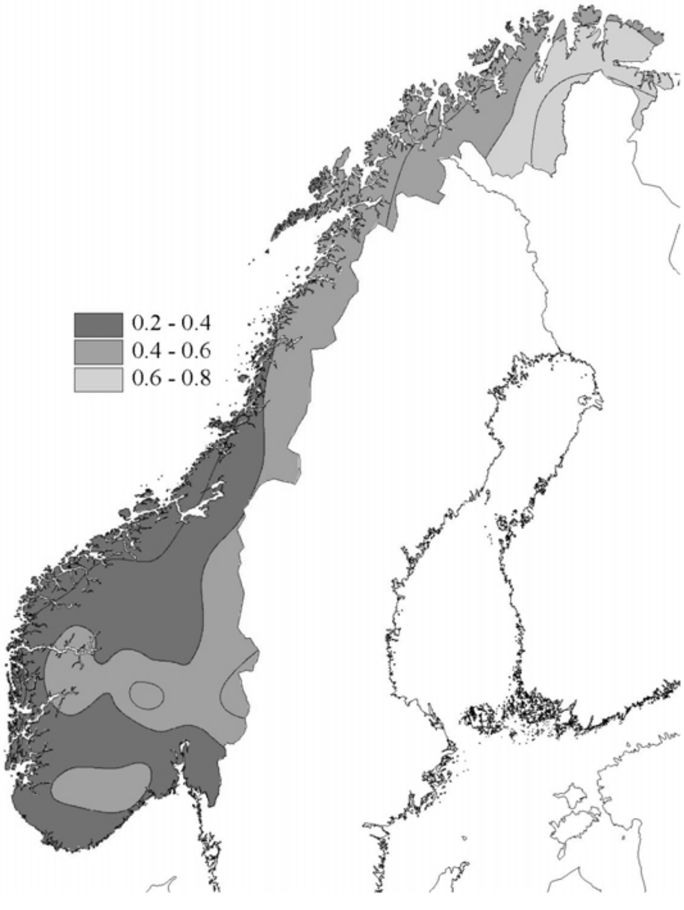

Figure 1 Empirically downscaled scenario showing the increase in winter temperature (winter = December–February). Values are the difference between the 2020–49 and 1961–90 periods and are given as change in °C per decade

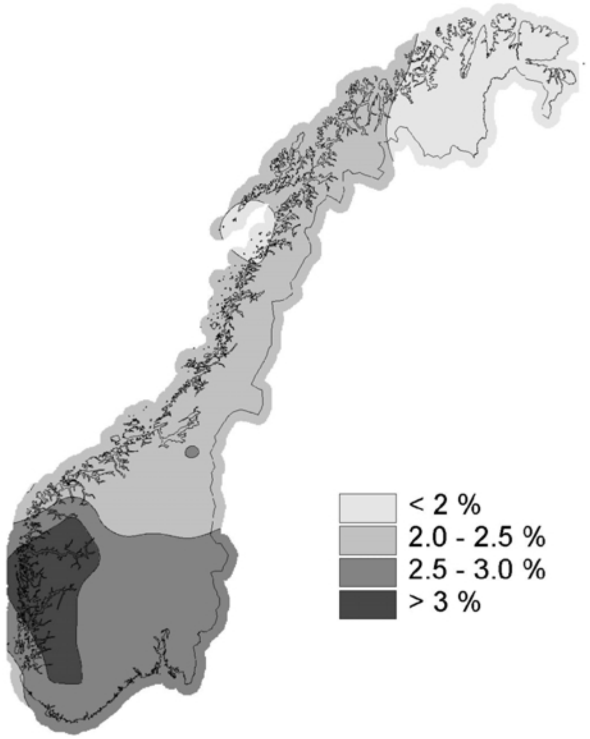

Figure 2 Empirically downscaled scenario showing increase in winter precipitation (winter = December–February). Values are the difference between the 2020–49 and 1961–90 periods and are given as changes per decade in percentage of 1961–90. The increase is larger than 1.5% per decade all over the country, and the largest increase is 3.4% per decade

over the next 50 years, making the climate more similar to conditions presently experienced in the middle of the country. In the south of Norway the expected increase in winter temperature is smaller, but this part of the country is still expected to experience a warmer winter climate in future, more similar to the current winter climate in Denmark and southern areas of Sweden.

Several sources of uncertainties exist related to both scenarios for global climate change, and to the effects of global warming on regional-level climate. Climate models differ in their indications of changes in the North Atlantic Ocean current (Gulf Stream) and in the extent of sea-ice cover in the Arctic. Changes in ocean currents and sea-ice will directly influence on the climatic conditions in Norway. The regional scenarios should not be considered as forecasts in an absolute sense. They offer insights into likely range and nature of future weather scenarios.

Impacts of climate change

Many sectors of Norwegian society may be affected by climate change. Impacts may be felt by economic sectors directly or indirectly dependent on climatic factors as well as environmental and social sectors. In the energy and hydropower sector, increased precipitation and runoff may enable increased power production. At the same time, however, increased temperatures are likely to reduce household space heating and energy demand (Sælthun, 1998). Present RegClim scenarios indicate that the growing season may increase by 20–30 days in large parts of the country up to 2050 (Skaugen and Tveito, 2002). A longer growing season and an expansion of area suitable for crop cultivation creates potential for increased yields, if optimal adaptations of the crop calendar and switching to suitable crop types are possible in the context of structural changes in Norway's agricultural sector (O'Brien *et al.*, 2002). The forestry sector may also see a lengthened growing season and an expansion of land available for forest production (Ministry of the Environment, 1991; Parry, 2000). On the other hand, warmer weather may increase the incidence of pests and diseases, soil erosion, poor snow cover and hoar frost, posing threats to forest and agricultural yields as well as to natural ecosystems (Sygna and O'Brien, 2001). The fisheries sector is sensitive to climatic changes in terms of fish stocks, introduction of fish species from the south, and the frequency of diseases (Loeng, 1995). Many communities in Norway depend on the fishery sector. Overfishing has been an important determining factor of fish stocks in the past and the interaction between stock management and climate change may be critical for the performance of this sector in future.

Few studies have examined the links between climate change and health in Norway, but studies in other parts of Europe suggest that health is sensitive to climatic events and changes. Health impacts occur via a variety of mechanisms, the direct impacts including heat- and cold-related illness and death related to thermal extremes and deaths, as well as injuries and psychological disorders related to other extreme weather events. In addition, indirect effects may occur, for example, as a result of disturbances in ecological systems and changes in geographic ranges and incidence of vector-borne diseases; in terms of respiratory disorders as a result of increased levels of air pollution, including pollen and spores; or in terms of mental health and nutritional impairment, infectious diseases and civil strife as a result of the effects of climatic changes on the economy, infrastructure and resource supply (Palutikof *et al.*, 1997; Parry, 2000). This is a useful area of further research. The maintenance of infrastructure and buildings is likely to become more costly with an increase in precipitation and wind and other meteorologically triggered events, such as hurricanes, floods, avalanches and landslides. Potential impacts and sensitivity of buildings and building enclosures are examined in more detail below.

Climate vulnerability in Norway

Definitions of vulnerability

Vulnerability is generally perceived to have both a physical and a social component. Chambers (1989 p.1) defines vulnerability as:

> the exposure to contingencies and stress, and difficulty in coping with them. Vulnerability thus has two sides: an external side of risks, shocks and stress to which an individual or household is subject: and an internal side which is defencelessness, meaning a lack of means to cope without damaging loss.

Coping refers to actions to ameliorate negative consequences (or capitalise on positive consequences) as climatic changes take place in order to maintain particular welfare goals, such as health, life and income (Eriksen *et al.*, 2002). The concept of exposure is also linked to social aspects through human reliance on resources affected by environmental events. A broader understanding of exposure employed by Downing *et al.* (1995) incorporates this internal structural side of exposure. This internal structural side is often known as sensitivity, the degree to which a system is affected by or responsive to climate stimuli (McCarthy *et al.*, 2001). For example, a society that relies heavily on agriculture may be more sensitive to climatic fluctuations than a society that depends solely on industry. In this paper, the social aspect of exposure is referred to as *sensitivity*, to be distinguished from *exposure*, which deals exclusively with the physical factors related to the probability of a climatic event, or change, taking place.

Norway can be considered a highly exposed country due to its extreme weather conditions (O'Brien *et al.*, 2002). The country's long coastline and steep topography make it particularly prone to extreme events like coastal storms, avalanches and landslides. In addition, Norway may be exposed to changes in autumn rainfall, and to an increase in the frequency and intensity of storms due to global warming. While the full range of impacts resulting from these changes remains uncertain, it is becoming clear that adaptation to climate change is necessary and inevitable. Adaptation to the prevailing climatic conditions has always been crucial for the viability of Norwegian society, but future climate changes may expose Norway to new challenges. Indeed, within the climate impacts literature, there is growing emphasis on adaptation and the need to enhance adaptive capacity, both in developed and developing countries (Kelly and Adger, 2000; Dolan *et al.*, 2001). Norway's sensitivity is potentially high due to the reliance of many of its economic sectors on climate dependent natural resources (O'Brien *et al.*, 2002).

What is adaptation?

Adaptation can be described as adjustments in practices, processes or structures to take into account changing climate conditions, to moderate potential damages, or to benefit from opportunities associated with climate change (McCarthy *et al.*, 2001). It is thus justified as a way of reducing the negative impacts of climate change and of taking advantage of the opportunities created by it. While the physical exposure component of vulnerability can be targeted through emissions reductions, it is, as argued above, likely to persist if not increase with climate change. In order effectively to reduce vulnerability, society's sensitivity and coping capacity must be targeted.

Coping can be distinguished from adaptation in that it refers to the immediate actions in the face of an event or changes and the ability to maintain welfare, whereas adaptation refers to long-term adjustments to the framework within which coping takes place (Adger, 1996; Eriksen *et al.*, 2002). Adaptation can be proactive and planned, involving conscious measures to meet anticipated changes, or it can consist of unplanned adjustments in response to changes that are not consciously designed to ameliorate the effects of climate change, but nevertheless affect sensitivity or coping capacity (Smit *et al.*, 2000; Eriksen *et al.*, 2002).

The built environment literally 'houses' economic activities, individuals and families, as well as society's cultural heritage. It is intended to protect life, health and psychological and social welfare of its inhabitants, host economic activities and undisturbed production and sustain aesthetic and cultural values. All these are central goals of coping capacity in the context of the built environment and in the face of climate change. The existence of an insurance system, described in more detail below, exemplifies a source of coping for people when a building is damaged by a meteorologically triggered event.

Potential impacts of climate change on building performance

Adaptation measures can involve household-level initiatives, construction industry initiatives and the various levels of public administration. The impact of climate change on the built environment will depend on the design, construction, use and location of buildings and building clusters. The most important government regulatory measures to ensure adherence to building codes and standards are the Technical Regulations under the Planning and Building Act. These regulations often refer to the Building Research Design Sheets in NBI's Building Research Series, with regards to solutions-in-principle for building structures. The location of buildings is regulated by various land-use planning tools available to governments. These will serve as valuable adaptation tools for governments as they plan for climate change. Considerable blame for the massive damages to buildings in central Europe after the floods of the summer of 2002 has been placed upon land use patterns. In an article in *New Scientist* (2002), it was argued that shortsighted land management has allowed global warming to wreak *havoc*, stating:

> ... the widespread building that has taken place on river flood plains across central Europe in recent years [that] is to blame for why the intense rainfall had such a catastrophic effect.
>
> (p. 4)

The regular insurance claims related to floods, as well as the intermittent large-scale destructions caused by floods, such as the 1995 floods in the south-eastern parts of the country, make land management a pertinent issue also in Norway.

While few studies have focused on the possible impacts of climate change on the built environment in Norway, impact studies in other countries show how vulnerable society becomes in the face of major climatic events and severe weather conditions. A British study (Graves and Phillipson, 2000) shows that an increase in wind speeds of 6% is likely to cause damage to 1 million buildings at a cost of £1–2 billion. The study also addressed the major impacts of increased driving rain quantities on the suitability of different types of building enclosures, and the likely increase of maintenance costs due to more extreme weather in parts of England. Dry summers in the south of England could lead to a 50–100% increase in subsidence claims in vulnerable areas.

A study published by the Building Research Association of New Zealand highlights climate change impacts on building performance in New Zealand (Camilleri *et al.*, 2001). It was concluded that the future performance of buildings in New Zealand may be significantly altered with regard to coastal and inland flooding, overheating, and wind damage and flooding associated with tropical cyclones.

The hurricane that hit Northwest Norway on 1 January 1992 caused severe damage to buildings. Large snow loads on roofs during the winter of 1999/2000 contributed to the collapse of several buildings in northern Norway. The roof structures of several buildings in parts of the country are thought to be far below current design standards and may be in danger of collapsing in the event of future heavy falls of snow. Eastern Norway and the southern coastal regions experienced extended periods of rainfall in the autumn of 2000. The heavy rainfall caused damage to buildings that had not previously been subjected to such damage.

Although neither of the above-mentioned weather events alone could be directly ascribed to climate change, events of that character are expected to increase in frequency under climate change. Extreme weather conditions are familiar to Norwegian society. However, there is a clear need to identify areas of vulnerability in the construction industry with regard to the potential impacts of climate change, and to develop and prioritise appropriate adaptation strategies.

Extensive degradation and damage to the built environment occur every year due to the impacts of precipitation, wind, temperature and exposure to the sun causes. An understanding of how degradation and damage can best be reduced is of significant importance to the design and construction of buildings. Future building materials, structures and building enclosures will likely need to withstand even greater climatic impact in parts of Norway than they do today. When designing building enclosures to resist wind actions, extremes are much more important than mean wind velocities. For certain types of house facings (e.g. rendered walls), the duration of rainy periods might be of greater importance than the maximum intensity of precipitation that occurs in the form of driving rain (combined rain and wind). For other types of external walls (e.g. board-clad walls), the intensity of driving rain may be the most important factor. The total number of freezing and thawing cycles is significant when the whole-life performance of masonry constructions is to be determined. For polymer materials, the sum of ultraviolet radiation may determine the lifetime of the products rather than the yearly averages in temperature. Many parts of buildings' external enclosures are likely to be subject to faster degradation in parts of the country where there is increased ultraviolet radiation.

The above examples illustrate the complex relationship between building materials, structures and climatic impact, and they also shed light on the need for more advanced and accurate methods of assessing building performance in relation to climatic impacts. The prospect of an even harsher climate in parts of the country means that we must pay more attention to the design, construction and geographical location of the built environment, and be more cognisant of the climatic-related impacts that buildings will have to endure. Hence, there is a clear need to develop further our knowledge, methods, tools and solutions in particular with respect to the planning and design of buildings in severe climates in order to ensure a reliable building stock in the future.

Adaptation strategies

Factors affecting adaptation options and capacity

The distribution of risk in society and people's control over their environment are related to the underlying economic and social situation (Adger, 1996). To understand the vulnerability of a particular society, sector or social group, it is necessary to analyse the factors and processes that determine why some people or businesses can cope, such as with damages caused by a cyclone, and others cannot. The built environment encompasses both domestic housing, industry and business premises. The building sector involves several actors, including occupants of the buildings (individuals and families, business, industry and the service sector), authorities who regulate the built environment, and the construction industry. Social agency does not operate in a vacuum: there is a range of factors influencing and determining what adaptation options are available to actors in the construction industry. We can divide these factors into three broad groups: political, economic and cultural, all of which are interlinked. Social factors may lead to inequality in building standards, in the ability to sustain social and psychological well being in the face of damaged housing, and in the ability to repair damage after the event. Political and economic processes also fundamentally affect sensitivity, in terms of settlement patterns, for example.

Politically, the dialectic between regulation and liberalisation is also important in the field of climate vulnerability. A government-appointed official committee stresses the challenge to the State in maintaining a proper security level for its citizens in a political environment increasingly characterised by liberalisation, market economy and privatisation (NOU, 2000). Institutions have looser attachments to the State, and this constrains the measures available to the state to secure a proper level of disaster preparedness in important sectors of society.

Economic trends and structures also affect adaptation options and practices in the construction industry, both at the demand and the supply sides. It is widely recognised that a corrupt construction industry, neglecting bylaws and technical regulations and building poor-quality structures, was partly responsible for the disastrous consequences of earthquakes in countries such as India and Turkey (*The Economist*, 2001; *New York Times*, 2001).

The demand for cost efficiency in the construction industry has in some cases contributed to the reduced robustness of Norwegian buildings. The hurricane that occurred in Northwest Norway in 1992 caused damage to buildings in the range of NOK1.3 billion. The total extent of the damage, including damage to building structures, was approximately NOK2 billion. Wind speeds of 62–63 metres per second were recorded, the highest wind speeds that have ever been recorded on mainland Norway. The bulk of the damage was incurred to roofs and roofing, due primarily to insufficient anchoring. Most of the damage could have been avoided had the existing Building Regulations and Codes of Practice been adhered to (National Office of Building Technology and Administration, 1993).

There are a number of 'intangible' cultural aspects that influence vulnerability and adaptation capacity, both through their influence on construction practices, building design and land-use planning, and locational decisions. People's preferences and demands for housing are changing as well as their perceptions of risk. We now find construction of both residential and commercial houses in areas that were not previously developed due to their high exposure to floods, landslides and avalanches, and the full force of wind gusts. Well-developed insurance schemes, increased pressure on land in already densely populated areas, and increased levels of private wealth may be among the causes of such risk taking. An additional factor is the inability to maintain and make use of local traditional knowledge about local climatic conditions. These issues deserve further research in order to increase our understanding of how adaptation may take place.

Adaptation pertinent to the construction industry can thus refer to; first, reducing sensitivity by making buildings more resistant to harsh weather and altering settlement patterns away from risky areas; and second, strengthening society's coping capacity. The latter refers to reducing trauma and economic damages when buildings or business premises are damaged or increasing the ability to capitalise from increased temperature and other climatic changes. While some adaptation measures can be undertaken by actors within the industry alone, the importance of addressing the underlying causes and constraints of both sensitivity and coping capacity means that these measures must be supplemented by ones that go far beyond the building sector.

Government initiatives addressing climate change adaptation

As mentioned above, no holistic or conscious strategy or policy for addressing these 'wider than sector' issues exists in Norway. In 1999, the government appointed an official committee to review Norway's social vulnerability and disaster preparedness. The committee presented its recommendations in July 2000 (NOU, 2000). The report defines natural disasters caused by extreme weather events, avalanches, storm surges or landslides as being among the challenges confronting Norway with regard to safety during normal peacetime. The report also stated that it was important to stress knowledge about the increased frequency and increased consequences of normal natural phenomena such as extreme weather conditions, floods and landslides, in which the consequences were made more severe as a result of pressure on the margins of safety in the building design process coupled with poor social and property planning.

Although the Norwegian Pool of Natural Perils addresses collective security and insurance, no climate change-related measures exist that target the underlying causes of sensitivity and coping capacity, or any of the factors constraining the institutional capacity to effect adaptation. Factors that deserve attention include institutional fit, interaction between institutions, goal conflicts and power relations, government incentive structures, and competing concerns within institutions (Næss, 2002).

Insurance

The Norwegian government has regulated the insurance market by establishing a risk-pooling mechanism in the case of natural perils, including climatically triggered extreme events. All insurance reimbursements for natural perils are covered by the Norwegian Pool of Natural Perils, which was established by Royal Decree in 1979 and is authorised by the Norwegian Act on Natural Perils from 1989. The Pool settles natural disaster damage compensation between companies and ensures the reinsurance coverage of Norwegian natural disaster insurance. In order to avoid individual assessments of the risk of natural perils and to provide adequate cover at reasonable premiums for those exposed to such risks, it was considered necessary to connect insurance against natural perils to an already existing form of insurance. Therefore, insurance against natural perils is a compulsory part of all fire insurance of objects and property in Norway, at present at 0.02% of the fire insurance premium. The risk pooling organisation of the industry in relation to natural perils makes the industry more robust in face of large natural disasters, contrary to other countries where individual insurance companies have to tackle such disasters alone. In Florida, US, for instance, Hurricane Andrew bankrupted nine small insurance companies and caused severe economic problems throughout the industry (Tucker, 1997; McCarthy *et al.*, 2001).

An additional advantage of the risk pool is that the Norwegian Pool of Natural Perils has a strong bargaining position vis-à-vis international reinsurance companies when they negotiate the price of reinsurance.

Preparing for adaptation in the built environment

There are a number of areas that need to be targeted in order to reduce the sensitivity of the built environment and thus vulnerability to climate change. Investigations carried out by the Norwegian Building Research Institute (NBI) have shown that the cost of repairs related to building damage in Norway amounts to 5% of the annual capital invested in new buildings (Ingvaldsen, 1994). Correcting faults and repairing damage to buildings during the construction process is estimated to cost roughly the same amount as repairing buildings in use, e.g. another 5% (Ingvaldsen, 2001). With an annual NOK130 billion being spent on building (as at 2000), it is therefore reasonable to estimate that approximately NOK13 billion is spent on repairing damage to buildings.

More than 75% of the building damage cases investigated by NBI were caused by external climatic impact (mainly due to moisture). About two-thirds of the damage is related to the design and construction of the building enclosure. In recent years, more attention has been paid to the negative implications that moist materials may have on indoor air quality and health. The link between dampness and health has been demonstrated scientifically by numerous epidemiological surveys. Such surveys are summarised in a Nordic research project (Bornehag *et al.*, 2001).

Historically, large variations in local climate have led to large variations in building practice throughout the country. The question is to what extent we have rejected sound building traditions and practice suited to local climatic conditions in our quest for standardised cost-effective solutions. The increasing demands in the construction industry for economy, progress and quality, combined with the existence of large amounts of precipitation during the construction process, prove to be a difficult circle to square.

A thorough review of the Norwegian built environment and infrastructure is needed in order to evaluate how different types of buildings and structures are vulnerable to the potential impacts of climate change. The 'robustness' of the Norwegian building stock and building practices should be assessed through analysis of statistical data, historical trends in the design and construction of buildings and built environments, and practical experience related to past building damage.

In Norway, the harsh climate means it is particularly important to take into account local climatic challenges. The basis for calculating characteristic wind and snow loads on buildings is regulated by Norwegian and international standards. At present there are no corresponding, easily accessible design guidelines for quantifying and sizing external and internal moisture loads. Thus, assessments of building structures' moisture safety levels will receive special attention in the Climate 2000 programme (Lisø *et al.*, 2002a). Climate change could have a major impact on the frequency of extreme weather events. The safety levels in Norwegian building regulations and codes with regard to undesirable incidents should therefore be reviewed regularly in order to maintain a proper level of reliability (Lisø *et al.*, 2000b). A related problem, demonstrated by the damages of the 1992 hurricane, is the inability to ensure that building codes are adhered to in practice. Ways to strengthen institutional capacity to implement appropriate building standards and codes of practice is an important element in adaptation to climate change.

In view of the above, it is likely that climate change will adversely affect property insurance. Norwegian insurance companies could be rendered vulnerable to climate change through changes in the frequency of storms and floods throughout the country. The construction industry's determination and ability to respond to climate change will be an important factor in the development of adaptation strategies. Strategies for climate change adaptation should be developed with due consideration for other agendas for change within the construction industry, including the general movement towards industrialisation, prefabrication and off-site construction (Lowe, 2001) (and the development of increasingly Europeanised construction and construction products industries). There are a number of actors and institutions that operate within the building sector and a high degree of interaction with other sectors and societal changes, but there remains a dearth of empirical studies on how these interactions affect climate change adaptation in Norway.

Research

Research funding in Norway is largely coordinated through the Research Council of Norway. In the past, climate-related research has been distributed among a large number of research programmes, including those on biodiversity, polar issues and energy-related issues. Lately, a restructuring of climate-related research has been taking place in Norway. The aim is to consolidate climate-related research into fewer programmes related to technological development, the natural science of climate change and the effects of climate change. The time horizon for most of these programmes (of the order of ten years) is intended to allow for a better structured and strategically sound planning of the research effort. A particular emphasis has been placed on the development of climate-friendly technologies in Norway and a substantial amount of money is to be spent on the development of technologies for reducing the CO_2 emissions from gas-fired power plants.

Although some studies have been funded to examine economic sensitivity, vulnerability and institutional adaptation, the main thrust of the research effort focuses on first-order physical effects of climate change on the environment, only indirectly addressing Norway's built environment. The construction industry is so far unique in having its own concerted programme of research specifically aimed at the possible impacts of climate change. This effort was, however, initiated and funded by NBI and the building and insurance sectors rather than the Research Council of Norway programmes. The research programme 'Climate 2000 – Building Constructions in a More Severe Climate' (Lisø *et al.*, 2002a), is being managed by NBI and carried out in cooperation with a large number of key actors in the construction industry. It was initiated in August 2000 and will continue to the end of 2006. The programme's principal objectives are to:

- Survey and increase knowledge about potential impacts of climate change on the built environment and how society can best adapt to these changes
- Develop and update methods, tools and solutions in principle for the planning and design of buildings (materials, structures and external enclosures) in order to increase both the durability and reliability in the face of external climatic impact
- Define more accurate criteria and codes of practice concerning building performance in severe climates

Conclusions and implications

Climate change will entail new conditions for several sectors of Norwegian society, including the construction industry. The climate system is likely to undergo changes, regardless of the implementation of abatement policies under the Kyoto Protocol or other regimes. While the full range of impacts resulting from these changes is still uncertain, it is becoming clear that adaptation to climate change is necessary and inevitable. A thorough review of the Norwegian built environment and infrastructure is needed in order to evaluate how different types of buildings and structures are vulnerable to the potential impacts of climate change.

Norway is considered to have a high adaptive capacity, based on macrolevel indicators such as wealth, technology, information, skills, infrastructure, institutions, equity, empowerment and the ability to spread risk (McCarthy *et al.*, 2001; O'Brien *et al.*, 2002; Yohe and Tol, 2002). Nevertheless, there have been few studies demonstrating that these factors will *de facto* lead to successful adaptation in Norway. Indeed, the entire process of adaptation is poorly understood at present. It is clear, however, that:

> [a]daptive capacity in human systems varies considerably among regions, countries, and socio-economic groups.
>
> (Smith *et al.*, 2001 p. 918)

There is a clear need to identify areas of vulnerability in the construction industry with regard to the potential impacts of climate change, and to develop and prioritise adaptation strategies. Both the functionality of the existing built environment and the design of future buildings are likely to be altered by the future impacts of climate change, and the expected implications of these new conditions must be investigated. However, measures aimed at adjustments in individual sectors, such as alterations of rules and specifications within the building sector, constitute only a partial adaptation to climate change. In order to develop necessary adaptation strategies, larger societal and intersectoral adjustments are crucial. There is an immediate need for information and research, both with respect to sensitivities in the built environment and technical solutions to climate impacts on buildings. Further, understanding needs to be enhanced with regard to the factors that shape the social landscape of the built environment and coping capacity, and the ways in which the building sector interact with other sectors as well as political, social and economic processes at large. There remains a lack of funding as well as appropriate codes and regulations. A move toward holistic policies and strengthened institutional capacity is needed to implement effective adaptation.

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Building enclosure performance in a more severe climate

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ABSTRACT: This paper gives an overall view of challenges concerning building enclosure performance in a potentially more severe climate, based on future climate development scenarios for different parts of Norway. Preliminary results from the Norwegian Research & Development Programme “Climate 2000 – Building constructions in a more severe climate” indicates that there is a clear need to further develop our knowledge, methods, tools and solutions in principal concerning the planning and design of buildings in harsh climates, in order to ensure a reliable building stock in the future as well. Climate change will entail new conditions for the Norwegian construction industry. The presented climate change scenarios calls for a systematically identification of areas in the Norwegian construction industry that are vulnerable to potential impacts of climate change, and the development of adaptation strategies.

1 INTRODUCTION

Observations increasingly point to global warming and other changes in the climate system. The Intergovernmental Panel on Climate Change concludes that most of the warming observed over the last 50 years is attributable to human activities, and that anthropogenic climate change will persist for many centuries (IPCC 2001).

Climatic impact from precipitation, wind, temperature and exposure to the sun causes extensive degradation and damage to the built environment every year. The understanding of how degradation and damage can best be reduced is of significant importance in the design and construction of buildings.

Future building materials, structures and external envelopes will probably have to withstand even greater climatic impact in parts of Norway than today. The trend we have seen over the last 10–15 years, with mild autumn-winter seasons with heavy precipitation and frequent storms along the coast, is expected to intensify.

Scientists in a wide range of disciplines are exploring the possible impacts of climate change. Until now, few studies have focused on the possible impacts of climate change on the built environment in Norway. In other countries impact studies have been performed along with studies of climate development under global warming. A British study (Graves & Phillipson 2000) shows that an increase in wind speeds of 6% is likely to cause damage to 1 million buildings at a cost of £1-2 billion. The study also addressed the major impacts of increased driving rain quantities on the suitability of different types of building enclosures, and the likely increase of maintenance costs due to more extreme weather in parts of England. Dry summers in the south of England could cause a 50–100% increase in subsidence claims in vulnerable areas.

A study published by the Building Research Association of New Zealand presents climate change impacts on building performance in New Zealand (Camilleri et al. 2001). The study concludes that future performance of buildings in New Zealand may be significantly different from the current performance with regard to coastal and inland flooding, overheating, and wind damage and flooding associated with tropical cyclones.

2 RESEARCH BACKGROUND

2.1 *Extreme weather events of the last ten years*

Coastal communities in Norway are vulnerable to strong winds. The hurricane that occurred in Northwest Norway on New Year’s Day 1992 caused damage to buildings in the range of 166 million Euro. Wind speeds of 62 - 63 m/s were recorded, the highest wind speeds that have ever been recorded on mainland Norway. The bulk of the damage was incurred to roofs and roofing, due primarily to insufficient anchoring.

Figure 1. Flooding in Risør, Southern Norway. October 2002 (photo: L. Aasbø, Agderposten).

Large snow loads on roofs during the winter of 1999/2000 contributed to the collapse of five buildings in Troms County in northern Norway. The accident at Bardufoss Community Centre in Troms County, where the roof caved in and claimed 3 lives, was the most serious of these accidents. Several roof structures in parts of the country are reckoned to be far below current design standards, and could be in danger of collapsing.

Eastern Norway and the southern coastal regions experienced extended periods of rainfall in the autumn of 2000. The heavy rainfall caused damage to buildings that had not previously been subjected to such damage.

2.2 *Social vulnerability and readiness*

None of the mentioned weather events alone could be directly ascribed to climate change, but they illustrate how vulnerable society is when faced with major climatic variations and severe weather conditions. Extreme weather conditions are familiar to the Norwegian society (Fig. 1). Still, there is a clear need to identify areas of vulnerability in the construction industry with regard to potential impacts of climate change, and to develop and prioritise adaptation strategies. The impacts of climate change, and potential strategies for adapting to climate change, represents some of the key challenges research faces in the coming years (IPCC 2001).

In 1999, the Government appointed an official committee to review Norway's social vulnerability and readiness. The committee presented their recommendations in July 2000 (NOU 2000:24). Their report defines natural disasters caused by extreme weather events, avalanches, storm surges or landslides as being among the challenges confronting Norway with regard to safety during normal peacetime.

The report also states that it is important to stress knowledge about increased frequency and increased consequences of normal natural phenomena such as extreme weather conditions, floods and landslides, in which the consequences are made more severe as a result of pressure on the margins of safety in the building design process, coupled with poor social and property planning.

3 THE NORWEGIAN BUILDING STOCK AND BUILDING PRACTICE

3.1 *Building damage in Norway*

Investigations carried out by Norwegian Building Research Institute (NBI) have shown that the cost of repairs related building damage in Norway amounts to 5% of the annual capital invested in new buildings (Ingvaldsen 1994). Correcting faults and repairing damage in buildings during the construction process is estimated to cost around the same amount as for repairing buildings in use (Ingvaldsen 2001). With an annual 13 billion Euro being spent on building, it is therefore reasonable to estimate that about 1.3 billion Euro is spent on repairing damage to buildings.

More than 75% of the building damage cases investigated by NBI have been caused by external climatic impact (mainly due to moisture). About two thirds of the damage are related to the design and construction of the building enclosure. In recent years, more attention has been paid to the negative implications moist materials have on indoor air quality and health. The link between dampness and health has been scientifically demonstrated by numerous epidemiological surveys. Such surveys have been summarised in a Nordic research project (Bornehag et al. 2001).

3.2 *Building practice*

Historically, large variations in local climatic impact have led to large variations in building practice throughout the country. The question is to what extent sound building traditions and practice suited to local climatic conditions has been rejected in our quest for standardised cost-effective solutions.

The increasing demands in the construction industry for economy, progress and quality, combined with the existence of large amounts of precipitation during the construction process, prove to be a difficult problem to overcome. Still, systematic evaluations of protection against moisture-related building damage have so far not drawn much attention in the construction industry.

4 CLIMATE CHANGE SCENARIOS FOR NORWAY

Scenarios regarding the climate development under global warming have been studied worldwide. The most realistic scenarios for changes in global climate are based on Atmosphere-Ocean General Circulation Models, AOGCM's (IPCC 2001). The spatial resolution in the recent AOGCMs is still too coarse to enable these models to reproduce the climate on regional or local scale. To deduce detailed scenarios for future climate development in different parts of Norway, both dynamic and empirical downscaling techniques have been applied on an integration ("GSDIO") with the Max-Planck Institute's global climate model ECHAM4/OPYC3. This is a transient integration up to year 2050, including greenhouse gases, tropospheric ozone, and direct as well as indirect sulphur aerosol forcings (Roeckner at al. 1999). In this integration, the concentration of greenhouse gases have been specified according to the IPCC IS92a scenario, with an annual 1% increase in CO_2 from 1990, giving a near doubling in concentration in 2050. The downscaled scenarios for Norway include climate elements such as temperature (2 m level), precipitation (solid and liquid amounts), relative humidity, solar radiation, wind speed, wave height, sea level, etc. Most elements are given with a time resolution down to 6 hours.

The empirical downscaled temperature scenarios (Hanssen-Bauer et al. 2000) indicate average annual warming rates of 0.2 to 0.5°C per decade up to year 2050 at the Norwegian mainland, and 0.6°C on Svalbard. The warming rates are generally smallest in southern Norway along the west coast. They increase when moving inland and northwards. At the west coast in southern Norway, the modelled warming rates are rather similar in all seasons (0.2-0.3°C per decade). Further north and in the inland region, considerably larger warming rates are found for winter than for summer. In northern Norway and inland valleys in southern Norway, winter warming rates of more than 0.5°C per decade are projected. Temperature scenarios for some Norwegian sites are presented in Table 1.

Table 1 also presents precipitation scenarios, deduced by empirical downscaling (Hanssen-Bauer et al. 2001). The scenarios indicate an increase in the average annual precipitation in Norway of 0.3 to 2.7% per decade during the next 50 years. The projected increase rates are generally smallest in southeastern Norway, and largest along the northwestern and western coast. In winter positive trends (1.8 to 3.2% per decade) are found all over the country. Also in autumn the precipitation increase (0.6 to 5.9% per decade) at most places, with the largest increase in western and northwestern regions. Modelled spring precipitation tends to decrease in southern Norway and increase in northern Norway, while the summer precipitation tends to decrease in eastern areas and increase in western areas.

Table 1. Empirically downscaled scenarios for changes in temperature and precipitation. The values are based upon the differences between the periods 1961-1990 and 2020-2049, and are given as changes per decade. (Winter = Dec-Feb, summer = Jun-Aug).

Location	Temperature change (°C/decade)			Precipitation change (mm/decade)		
	W*	S*	A*	W*	S*	A*
Lillehammer	0.40	0.29	0.32	2.8	-2.6	2.0
Oslo	0.37	0.26	0.30	3.8	-2.8	2.3
Oksøy	0.32	0.22	0.25	8.2	-3.1	6.8
Stavanger	0.33	0.27	0.29	7.7	0.3	20.7
Bergen	0.28	0.28	0.28	18.5	8.0	56.3
Trondheim	0.34	0.25	0.27	4.8	2.1	20.4
Bodø	0.43	0.36	0.41	5.0	-0.7	27.5
Tromsø	0.48	0.28	0.39	5.9	-0.6	29.2
Karasjok	0.79	0.33	0.51	0.9	0.3	5.1

*W = Winter, S = Summer, A = Annual

Table 2. Dynamically downscaled scenarios for changes (%) in frequencies of wind speeds above 15 m/s, six-hourly precipitation intensities above 10 mm, and six-hourly snowfalls exceeding 5 mm water equivalent. The values are based on differences in 6-hourly frequencies between the periods 1980-1999 and 2030-2049 for a limited number of grid points in each region (from Haugen & Debenard, 2002).

Region	Wind speed > 15 m/s	Precipitation >10mm/6h	Snowfall >5mm/6h
Oslo area	0	27	7
Western Norway (coast)	10	41	-27
North-western Norway (coast)	11	24	-25
Mountain regions, S. Norway	0	33	8
Nordland (coast)	18	11	-20
Troms, West-Finnmark (coast)	28	25	-11
East-Finnmark (coast)	41	50	33

Dynamically downscaled scenarios for changes in wind conditions (Haugen & Nordeng 2001) show a zone with increased mean annual wind speed from south of Iceland eastwards towards Fennoscandia. For Norway the changes in annual wind speed are small, with largest increase (~3%) in coastal areas in Western Norway, and along the coast of Finnmark county. High wind speeds are connected to the low-pressure activity over Northern Europe, and an increased frequency of wind speeds above 15 m/s is found along the Norwegian coast (see Table 2). In northern regions (Nordland, Troms and Finnmark county) the analysis indicates a rather significant increase in frequencies of strong winds in coastal areas, but for these regions the uncertainty in the scenarios is particularly large.

Scenarios for climatic extremes are presently being developed in the Norwegian RegClim-project (Regional Climate Development under Global Warming, see www.nilu.no/regclim). The preliminary results (Haugen & Debenard 2002) indicate a rather strong increase in frequencies of heavy rainfall, and a decrease in heavy snowfall episodes in low-elevation areas (see Table 2). Freezing and thawing events were analysed by studying a number of successive 6-hourly values where the temperature passed 0°C, and for most regions a general decrease was found (Haugen & Debenard 2002).

5 IMPACTS OF CLIMATE CHANGE ON BUILDING ENCLOSURE PERFORMANCE

5.1 *Introduction*

Climate change will have different climatic impacts on different types of buildings depending on scale, use, design, construction and location. When designing building enclosures to resist wind actions, extremes are much more important than mean wind velocity values. For certain types of house facings (e.g. rendered (plastered) walls) the duration of rainy periods might be of greater importance than the maximum intensity of precipitation that occurs in the form of driving rain (combined rain and wind). For other types of external walls (e.g. board-clad walls) the intensity of driving rain may be the most important. The total number of freezing and thawing cycles is significant when the whole-life performance of masonry constructions is to be determined. For polymer materials the sum of ultraviolet radiation may determine the lifetime of the products, rather than the yearly averages in temperature. Many parts of buildings' external enclosures are likely to be subject to faster degradation in parts of the country, for example due to increased frost occurrence or ultraviolet radiation.

These few examples are given to illustrate the complex relationship between building materials, structures and climatic impact, and to illustrate the need for more advanced and accurate methods for vulnerability assessment of building performance in relation to climatic impacts.

An overall view of building physics challenges concerning the design of roofs and façades is given in the following sections.

5.1.1 *Roofs*

5.1.1.1 Pitched insulated roofs

The traditional type of roof for single-family houses in Norway are ventilated and insulated pitched roofs (illustrated in Fig. 2). The purpose of ventilating such roofs is to avoid damage to the roof structure due to indoor moisture and/or built-in moisture being accumulated in the roof, and to keep the roofing cold so that melting snow, damaging icing and water retention can be avoided. Accumulation of moisture may be caused by condensation problems, rain water and air leakage through minor cracks in the structure, or diffusion.

Figure 2. The traditional type of roof for dwellings in Norway are ventilated and insulated pitched roofs (photo: K.R. Lisø).

Norwegian building tradition places great emphasis on the ventilation of insulated pitched roofs. Still, the need for and design of such ventilation has been a subject of discussion and varying practice for a number of years. This is particularly true for the height of the air gap itself and the size of gap openings (air inlets and outlets) at the eaves, ridges and gables. However, it has proved difficult to provide detailed and general guidelines for the design of air gaps and gap openings. The need for ventilation depends on how much heat is transferred through the roof structure, drying requirements, indoor and outdoor relative humidity, the shape, angle and surface area of roofs, and local climatic conditions such as wind speed, amount of snow on the roof, outdoor temperatures, sun exposure and long wave radiation exchange between the roof surface or the snow cover and the atmosphere.

In exposed, cold districts of Norway, driving rain and snow penetration at roof eaves and ridges can be a direct cause of moisture problems occurring in roof structures. The problem is most visible in areas with large amounts of precipitation and high wind speeds. Normally there is a clear need for air gaps and openings, for reasons discussed here. For reasons of penetration by precipitation and preventing the spreading of fires, air gaps and openings should however be no larger than absolutely necessary. In particularly affected areas, snow penetration problems are often solved by closing all air gap openings, trusting that necessary ventilation will be ensured by air leakiness through small unintentional air gaps in the roof structure. Such proofing can however lead to insufficient ventilation, poor indoor climate and the formation of dampness and mould. The protection of gap openings against snow penetration should be based on local experience from particularly weather-beaten districts in Norway.

Figure 3. The present design criteria for air gaps have been found to be the risk of ice formation on roofs caused by melting snow (photo: Y.O. Sæbbe, Nordlys).

The amount of building damage on roofs is closely connected with a complicated roof design, insufficient venting (narrow ventilation ducts under the roofing) and other inadequate details. Roofs are not only being exposed to external climatic loads and mechanical stresses. It is also important to understand the impacts of the indoor environment on the design of constructions, especially the air tightness of roofs and outer walls. One of the most common causes of failure in the design of roofs is air leakage from the inside - with subsequent condensation problems. This is especially true when it comes to roofs covering rooms with severe moisture loads. Buildings with large roofs (more than 7 meters from eaves to ridge) and high headroom often experience moisture problems because the same roof design principles are being used as for smaller buildings (e.g. single-family houses). The problems are primarily related to insufficient ventilation of larger roofs, and the consequences are likely to be more severe for these roofs than for smaller roofs.

Changes in amounts of precipitation could influence the whole-life performance of roofs. An increase might change the performance requirements of the roofing, the ventilation air gaps and the underlay for roofing. The present design criteria for air gaps have been found to be the risk of ice formation on roofs caused by melting snow (Blom 1990, 2001) (Fig. 3). The design criteria are valid provided the airtight layers (the vapour retarder and the wind barrier) are performing sufficiently. Increasing the thickness of the insulation will decrease the transfer of heat through the roof surface and the likelihood of melting snow. The thermal insulation and continuous wind and vapour barriers in the roof are also deciding factors regarding the prevention of ice formation.

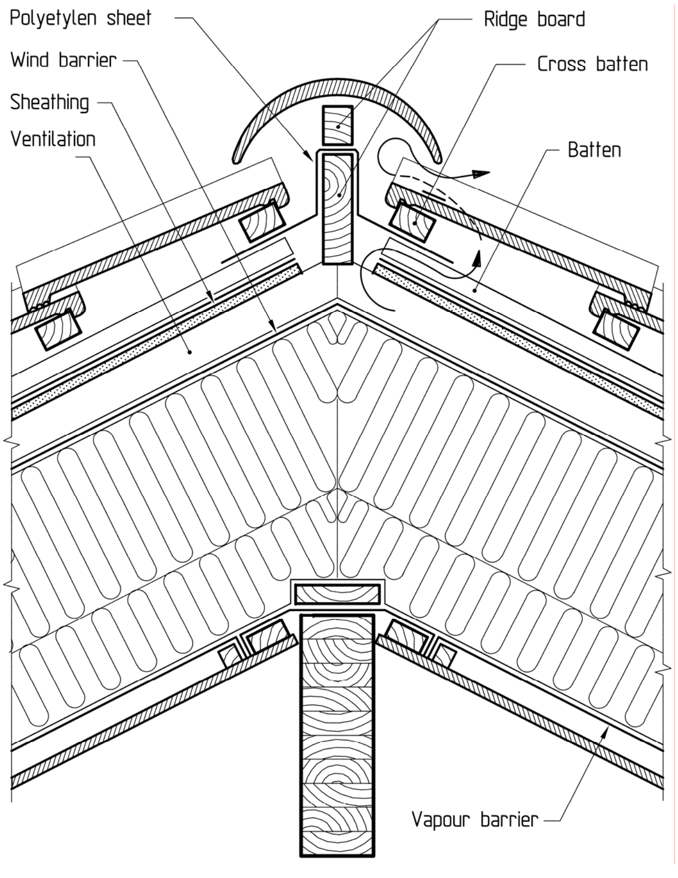

Figure 4. A modern pitched insulated roof construction with separate wind barrier and sheathing.

The amount of moisture damage in larger pitched roofs calls for a more reliable moisture-proof roof design. Pitched roofs should be insulated continuously from ridges to eaves, and not have partly insulated attics which in practice does not get cold enough to avoid ice formation on the roof. Ideally, roofs should have all thermal insulation placed on the cold side of the roof's load-bearing structures.

Organic materials within the insulation layer that could be damaged by moisture ought to be avoided. The traditional way of ventilating an insulated pitched roof is the use of an air gap underneath the underlay for roofing (to ensure sufficient venting of excessive moisture) and one air gap above the underlay for roofing (to prevent melting snow), illustrated in Fig. 4. New materials, like the combined underlay for roofing and wind barrier (watertight breather membrane), have led to a design of roof structures where all the ventilation of the roof surface takes place through an air gap between the roofing and the underlay for roofing. This is still a rather new roof design in Norway, introduced back in the 1980's. The Norwegian construction industry has not fully adapted this solution, mainly due to a profound scepticism concerning water tightness under severe weather conditions. Larger amounts of precipitation in parts of the country could entail more scepticism.

This expresses the need for more comprehensive investigations on issues concerning ventilation and drying of pitched insulated roofs.

5.1.1.2 Compact roofs

Compact roofs are roofs where the different layers of materials are placed close to each other without ventilated layers. These roofs normally have a water- and vapour-tight roofing membrane on top of the insulation and a vapour retarder on the inside, and thus limited drying properties. Compact roofs are built as both flat roofs (angle of pitch of roof < 6°) and pitched roofs (angle of pitch of roof > 6°). As far as larger buildings are concerned, this is the dominant type of roof structure. Compact roofs are used on all sorts of buildings, and properly constructed compact roofs rarely sustain damage.

Built-in moisture in compact roofs is a topic that once again became of great interest following the mentioned extreme rainfall in the autumn of 2000 in eastern Norway. Heavy precipitation during the construction period increases the risk of built-in moisture during roof construction. The development of weather-protective measures (e.g. tent solutions) and guidelines for the construction phase will be of great importance.

5.1.2 *Façades*

5.1.2.1 Definitions

External walls should be designed to form a climatic envelope against the surrounding environment, in order to ensure the desired indoor climate. Façade materials and systems, as well as the correct design of construction details, is therefore of crucial importance as far as the functionality and lifetime of buildings are concerned. Driving rain represents the greatest challenges concerning the design and construction of outer wall structures. Façades or outer walls are also exposed to moisture impact from the indoor environment.

External wall structures can be divided into systems with one stage tightening (massive façades/outer walls) and systems with a two stage tightening (ventilated façades/outer walls). The design requirements depend on many factors, but the local climatic conditions at the building site are of crucial importance.

5.1.2.2 One stage tightening

Field and laboratory tests have been carried out to analyse whether the current design and construction practice for rendered masonry façades (one stage tightening) in Norway provides sufficient protection against moisture-related problems. The impacts of structure and composition of rendering layers have been studied through laboratory tests (rain tests in field testing) (Kvande & Waldum 2002a, b). This experimental programme emphasised the importance of the type of binder to obtain an optimal water tightness of a rendering system. A cement-rich mortar should always be used as spatter dash to resist water penetrating the wall. A two-coat render is not sufficient to withstand heavy driving rain, and so a three-coat system has to be used. The final coat in a three-coat render may be a suitable inorganic coat like silicate paint. The results are of special interest for massive masonry walls, and for masonry walls without sufficient ventilation.

5.1.2.3 Two stage tightening

The principle of façade systems with separate wind and rain barriers was thoroughly studied in Norway in the 1960's. The principle was introduced in order to achieve better weatherproofing of façades and façade elements. A two stage waterproof façade has the principle design of an outer rain protection layer, a ventilated and drained space and an airtight layer. The outer rain protection layer, i.e. the cladding, could be different kinds of wood panelling, metal sheeting or board claddings. The rain protective properties are dependent on the type of material, the number of joints and the performance of the joints. Detailed experimental studies were conducted in Norway in the mid 1960's (Birkeland 1963, Isaksen 1966), and the results are still applicable.

More precipitation in the form of rain (or all forms of water originating from the atmosphere) will to a greater extent challenge the performance of ventilated claddings. The surrounding drying conditions will most likely be worse, even with small increases in temperature.

Wood is the most common cladding material for dwellings and smaller buildings in Norway. The performance of a wooden cladding depends largely on the quality of the wood material, the surface coating and the construction details. The recommendations for use of wood as cladding material has been unchanged for many years, though there are arguments claiming that an air space between the cladding and the wind barrier might not always be necessary.

Gypsum boards are often used as airtight sheathing in buildings. A vapour permeable and water repellent membrane (breather membrane) are often recommended for buildings being erected in coastal areas, in addition to the gypsum board. Further studies on the mechanisms of ventilation and drainage of different outer wall constructions in different climate zones will be carried out, in order to better understand the necessity of water vapour resistance of wind barriers. The studies will be based on Geving & Uvsløkk 2000.

Increasing amounts of precipitation and severe driving rain conditions will put the current construction practice for brick veneered walls to test. Laboratory tests carried out by Kvande (1994) demonstrates the capability of such walls to withstand extreme driving rain conditions as long as the performance matches the current requirements. Efficient ventilation behind the outer leaf has to be ensured in brick veneer wall constructions to resist driving rain, and to avoid moisture damage. There will always be possibilities for rainfall to penetrate the outer leaf. Hence, a drainage system is also necessary to ensure that water penetrating the outer leaf is effectively drained.

6 THE WAY FORWARD

6.1 *The Climate 2000-programme*

The prospect of an even harsher climate in parts of the country means that we must pay more attention to the design, construction and geographical localisation of the built environment, and be more aware of the climatic impact buildings will have to endure. Hence, there is a clear need to further develop our knowledge, methods, tools and solutions in principal concerning the planning and design of buildings in severe climates, to ensure a reliable building stock in the future.

This forms the background for the initiation of the Norwegian Research & Development Programme "Climate 2000 – Building constructions in a more severe climate" (Lisø et al. 2002). The programme, which consists of 14 different projects, is being managed by NBI and carried out in cooperation with a large number of key actors in the construction industry. It was initiated in August 2000, and will continue until the end of 2006.

The programme's principal objectives are to:

- Survey and increase the knowledge about possible impacts of climate change on the built environment and how society can best adapt to these changes.
- Develop and update methods, tools and solutions in principal for the planning and design of buildings, resulting in both increased durability and reliability in the face of external climatic impact.
- Define more accurate criteria and Codes of Practice concerning building performance in severe climates.

Both the functionality of the existing built environment and the design of future buildings are likely to be altered due to possible impacts of climate change, and expected implications imposed by these new conditions will be investigated.

6.2 *Review of the Norwegian building stock and building practice*

A thorough review of the Norwegian building stock and building practice will be carried out within the Climate 2000-programme, to evaluate how different types of buildings and structures are vulnerable to possible impacts of climate change. The "robustness" of the Norwegian building stock will be assessed through analysis of statistical data, along with NBI's experience related to building damage. Statistical data for building types, year of construction, material use, building and construction design and geographical localisation are available. Historical trends in the design and construction of buildings and built environments will also be studied. Historical weather data and statistical data from insurance companies (natural damage) will serve as a basis for the analysis.

Information on all these elements needs to be elaborated systematically. Geographic Information Systems (GIS) tools will be implemented for the assessment, mapping and presentation of climate change risk factors. Risk and vulnerability assessment methods concerning building performance in a potentially more severe climate will also be developed. This work will include development of methods for classifying different climate parameters and their impact on buildings, and the preparation of a thorough overview of the relevant climate variables that should be taken into account during the planning, design, construction, management, operation and maintenance of the built environment. A Climate Index Approach for selecting Design Reference Years, as a basis for the improvement of advanced modelling tools (e.g. computational fluid dynamics applications), are now being considered. Historical weather data will be compared with climate change scenarios for different parts of Norway, and the scale of impacts derived from this analysis.

6.3 *Adaptation strategies*

In Norway, there are many weather-beaten areas where it is particularly important to take into account local climatic challenges. The basis for calculating characteristic wind and snow loads on buildings is regulated by Norwegian and international standards. At present there are no corresponding, easily accessible design guidelines for the quantifying and sizing of external and internal moisture loads. Thus, assessments of building structures' moisture safety levels will receive special attention in the Climate 2000-programme. Climate change, building performance and standardisation will be discussed through established networks within the International Organization for Standardization (ISO), the European Committee for Standardization (CEN) and our co-operation with the Norwegian Council for Building Standardisation. Climate change could have a major impact on the frequency of extreme weather events. The safety levels in Norwegian building regulations and codes regarding undesirable incidents should therefore be reviewed regularly in order to maintain a proper level of reliability.

The importance of scale is considered key to understanding and addressing climate change impacts and vulnerability. Assessments of vulnerability, sensitivity, robustness and resilience are scale-dependent, and it would be misleading to extrapolate climate change scenarios and assessment results across scales (i.e. whether impacts are assessed at a national, regional or a local level) (O'Brien et al., in press).

It is likely that climate change will adversely affect property insurance. Insurance companies could be vulnerable to climate change through changes in frequency of storms and floods. The construction industry's determination and ability to respond to climate change will be an important factor in the development of adaptation strategies.

Strategies for climate change adaptation should be developed with due consideration for other agendas for change within the construction industry, including the general movement towards industrialisation, prefabrication and off-site construction (Lowe 2001).

7 CONCLUSIONS

Climate change will entail new conditions for the Norwegian construction industry. Knowledge about the implications of climate change on building enclosure performance will be of the utmost importance to the industry in the years to come.

The built environment has an expected lifetime from 60 to more than 100 years. The potential implications of climate change over the next decades should therefore be considered when constructing buildings today. We believe that future building regulations and codes should not only be based on historical weather data, but also on future climate development scenarios. This is particularly important with respect to the preparation of Norwegian appendices to national and international standards associated with the various types of climatic impact.

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A primer on the building economics of climate change

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Climate change will entail new conditions for the construction industry. Knowledge about the implications of climate change on the built environment will be of the utmost importance to the industry in years to come. A building is a 'long lasting' durable asset that is changed over time due to exogenously imposed strains and by actions. The built environment has an expected lifetime varying from 60 to more than 100 years. Hence, the building economics of climate change should be treated within a dynamic analytical framework that explicitly allows for changes in the information sets over time. The building stock of the future consists of the building stock of today and of new construction. In the future, parts of the present building stock will be adapted to changes in the environment, while some parts will be kept as they are. Analysis of how building stock is affected by future climate change should handle this diversity. This can be done through the use of a putty-clay model. Uncertainty of what kind of climate regimes will prevail in the future enhances the profitability of actions that increase future flexibility. Hence, the real option approach to building economics is utilized.

Keywords: Building economics, global warming, climate change, putty-clay, real options, building stock, building enclosure performance

Introduction

Empirical observations and modelling increasingly point to global warming and long-term changes in the climate system. The Intergovernmental Panel on Climate Change concludes that most of the warming observed over the last 50 years is attributable to human activities, and that anthropogenic climate change is likely to persist for many centuries. The ability to respond to climatic change in terms of averting negative consequences and capitalizing on any potential benefits arising from it is central to managing vulnerability (Lisø *et al.*, 2003a).

Climatic impact from precipitation, wind, temperature and exposure to the sun causes extensive degradation and damage to the built environment every year. This can be related to variations over normal everyday impact from different climate parameters, and it can be related to more extreme and less frequent climatic events. Climatic impacts affect operating costs and maintenance. The design of building enclosures should be expected to be the result of choices based on optimally utilized information and knowledge on both building technology and the different impacts the buildings are exposed to. An increase in the knowledge about, and focus on, the impacts of different climatic parameters on building enclosure performance will lead to a more climate-adapted design in new construction. Utilization of this kind of knowledge also gives a potential for a more robust performance of existing buildings. A more focused attention on climatic impact will also contribute to a higher level of reliability in buildings, extended lifetime, reduced administration, damage and maintenance costs through correct planning and design. The design of one single building is primarily affected by the stock of knowledge at the point in time where the building was erected. However, buildings are adapted, maintained and rehabilitated over time. Hence, the present state of a building will also be affected by knowledge, both on building technology and expected strains, which has arrived during the time after completion.

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The topic of this paper has not been much studied using tools from economic theory. Central issues for us are to survey the possible impacts of climate change on the building stock and the behaviour of building owners. Hence, as the title indicates, the paper is a primer on the building economics of climate change rather than providing final empirical answers. Furthermore, we have focused on the microeconomics of impact on and adaptation of single buildings. Aggregation will be treated at a later stage. At the outset, we will stress that even though the paper is purely theoretical, it has an empirical ambition.

Analysing the building economics of climate change

Climate vulnerability in general

While few studies have focused on the possible impacts of climate change on the built environment in Norway, impact studies in other countries show how vulnerable society becomes in the face of major climatic events and severe weather conditions. A British study (Graves and Phillipson, 2000) shows that an increase in wind speeds of 6% is likely to cause damage to 1 million buildings at a cost of £1–2 billion. The study also addressed the major impacts of increased driving rain quantities on the suitability of different types of building enclosures, and the likely increase of maintenance costs due to more extreme weather in parts of England. Dry summers in the south of England could lead to a 50–100% increase in subsidence claims in vulnerable areas.

A study published by the Building Research Association of New Zealand highlights climate change impacts on building performance (Camilleri *et al.*, 2001). The study concludes that the future performance of buildings in New Zealand may be significantly altered with regard to coastal and inland flooding, overheating, and wind damage and flooding associated with tropical cyclones.

Climate vulnerability in a Norwegian context

Norway can be considered a highly exposed country due to its extreme weather conditions (O'Brien *et al.*, 2003). The country's long coastline and steep topography make it particularly prone to extreme events like coastal storms, avalanches and landslides. In addition, Norway may be exposed to changes in autumn rainfall, and to an increase in the frequency and intensity of storms due to global warming. While the full range of impacts resulting from these changes remains uncertain, it is becoming clear that adaptation to climate change is necessary and inevitable. Adaptation to the prevailing climatic conditions has always been crucial for the viability of Norwegian society, but future climate changes may expose Norway to new challenges (Lisø *et al.*, 2003a).

Future building materials, structures and building enclosures will likely need to withstand even greater climatic impact in parts of Norway than they do today. When designing building enclosures to resist wind actions, extremes are much more important than mean wind velocity values. For rendered walls, the duration of rainy periods might be of greater importance than the maximum intensity of precipitation that occurs in the form of lashing rain. For board-clad walls, the intensity of driving rain may be the most important. The total number of freezing and thawing cycles is significant when the whole-life performance of masonry constructions is to be determined. For polymer materials, the sum of ultraviolet radiation may determine the lifetime of the products, rather than the yearly averages in temperature. Many parts of buildings' external enclosures are likely to be subject to faster degradation in parts of the country where there is increased ultraviolet radiation (Lisø *et al.*, 2003b). The prospect of an even harsher climate in parts of the country means that we must pay more attention to the design, construction and geographical location of the built environment, and be more cognisant of the climatic-related impacts that buildings will have to endure.

Buildings and potential impacts of climate change

Several sources of uncertainty exist related to both scenarios for global climate change, and to the effects of global warming on regional-level climate. The regional scenarios, therefore, should not be considered as forecasts in an absolute sense, but they do offer insights into likely range and nature of future weather scenarios (Lisø *et al.*, 2003a). The climatic impact that a single building is exposed to over a limited period of time can be described as a stochastic process. The less than perfectly known regional climate development under global warming can consequently be described as a stochastic process that selects among climate generated processes, or climate change scenarios. The perceived characteristics of this climate-generating process can change over time, i.e. the different actors in the construction industry and in the real estate market are assumed to be able to learn.

Scenarios for future climate change at the very local level are highly uncertain. However, buildings are located and they are affected by weather related strains. Owners will consequently have to adapt to the expected climatic environment at the very place where the building is located.

Introducing the analytical framework

The potential implications of climate change on the building stock can be addressed at different levels:

- How will the performance and cost of operating of existing buildings be affected by climate change, if the buildings characteristics are kept unaltered?
- How should existing buildings be adapted to changes in the stream of weather related strains that hits the building enclosure. At what cost can this be done for, and when should it be done?
- How will the technical lifetime of buildings be affected by climate change? What about the economic lifetime?
- How will the choice of technology, materials and design in new construction be affected?
- How will (the time path of) the level of new construction be affected?

The analytical framework developed in this paper is, in principle, intended to be applicable at all these levels. In fact, we will claim that these levels are nested within each other.

In order to illustrate the importance of the abovementioned issues, think about the distinction between a long-run and a short-run equilibrium in the property market. Assume that we experience a (perfectly observed) shift from one 'stable' climate regime to another 'stable' climate regime. This changes the optimal design of buildings. However, one does not start from scratch. When the shift is experienced, a building stock already exists. The existing building stock will be less suitable than newly constructed buildings under the new climate regime. Nevertheless, for the larger part of the building stock it will be profitable to continue the use. The economic lifetime of existing buildings will, in part, depend on their adaptability to changed climate conditions. Given the durability of the building stock, the time before the whole building stock is optimally adapted to a new climate regime can amount to a hundred years or more. Hence, John Maynard Keynes' famous remark – 'In the long run, gentlemen, we are all dead' – really applies to the process of adjustment towards a new long run equilibrium building stock, following a potentially more severe climate.

An analysis of the building economics of climate change should, consequently, not confine itself to addressing the questions of how new buildings are and ought to be affected. On the other hand, the analysis should not be confined to investigations of how the existing building stock, without any adaptations taking place, is affected by changed occurrence of climate related strains. An economic analysis, of course, should address the question of how choices are affected by changes in the framework under which decisions are taken and by initial endowments. Changes in the climate system are part of 'the framework under which decisions are taken' and the existing building stock is part of 'the initial endowments'.

A building is a very 'long lasting' durable asset that over time is changed due to exogenously imposed strains and by actions taken by different stakeholders. Analysis of how buildings will be affected by climate change should consequently be done within a dynamic analytical framework that explicitly allows for changes in the information sets over time. The analysis should result in descriptions of the expected time paths of the state of the building stock and of measures taken to adapt.

The building stock some time into the future consists of the building stock of today and of the new construction of the future. Parts of the present building stock will in the future be adapted to changes in the environment, while some parts will be kept as they are. Analysis of how the building stock is affected by climate change should handle this diversity. We propose that this diversity should be treated within the framework of some kind of vintage model. Formulation of such a vintage model involves complex problems of (non-trivial) aggregation. A central tool in this aggregation will be considerations of how the value in use of different parts (or classes or vintages) of the existing building stock are expected to evolve over time as improved and more reliable climate change scenarios are developed. Before the questions of aggregation, or formulation of vintage models, are addressed one should concentrate upon how the potential impacts on single buildings should be identified. In other words, before aggregation is treated we need to focus on the mechanisms that are to be aggregated.

The putty-clay and the real option approaches

The paper proposes a way of analysing the building economics of climate change that is based on two pillars or approaches. Firstly, it is the putty-clay approach to the theory of investment and production. The main starting-point for this is that the scope for choosing different designs of a building is far broader before than after the building is erected. Hence, a building consists of elements that are costly to change once the building is erected, and of elements that can be more easily maintained. The putty-clay approach dates back to Johansen (1959).

The other pillar of our analysis is the real option approach. In short, one can say that this approach highlights the fact that information relevant for decision makers arrives over time. Immediate decisions should take into account that they affect possible actions taken into the future and their profitability. In other words, immediate decisions affect the value of real options.

Impacts of climate change on buildings: a two-dimensional description of the value of a building

Here we analyse stylized models of the choices made by the owners under different sets of simplifying assumptions. A building is a complex asset that can be described along an almost infinite number dimensions. We simplify this into a two-dimensional description, and we proceed by assuming that the value of a building (V) depends on these two factors. The two factors are one fixed component Φ and one variable component, z^t.

$$V = \sum_{t=1}^{r} d^t v^t(\Phi, z^t) \tag{1}$$

where d^t is a time dependent discounting factor and $v^t()$ is a kind of production function.

The production function is assumed to exhibit a putty-clay structure. A putty-clay production structure is a structure where the substitutability between production factors is larger before an investment takes place than they are after the investment is made. The putty-clay approach is used in general studies of investment by, among others, Johansen (1972) and Moene (1984). Here it means that once the building is completed the characteristic, Φ. is fixed. The production factor z^t can be varied according to the technology $g^t()$:

$$z^t = g^t(\Phi, z^{t-1}, x^{t-1}, m^t) \tag{2}$$

where x^{t-1} is the uni-dimensional strains (amongst other things climatic impacts) that the building experience through period $t-1$, accumulated up to the start of period t, and m^t is the effort made to increase the value of the variable production factor at t. One can think of this effort as maintenance.

The production function $g^t()$ plays a crucial role in the analysis of the choices made by building owners as a dynamic link between the efforts of any period and the future performance and need for effort/maintenance of the building. The costs of operating the building ($c^t()$) depend on the state of the building and the strains that the building is exposed to during a given period (e.g. impacts of different climatic parameters on the everyday operation of the building, including energy use):

$$C^t = c^t(\Phi, z^t, x^t) \tag{3}$$

The strains a building is exposed to are stochastic. The outcome of the stochastic process is assumed to be multinomial distributed over a finite set of outcomes. The outcomes are uncorrelated over periods. The probabilities of each of the states that produce outcomes can change over time. Throughout the rest of the paper, we will think about the decision maker, who in this paper is the owner, as being risk neutral. Hence, it is assumed that the owner maximizes the expected net present value NV of the building:

$$NV = \sum_{t=1}^{T} \sum_{s=1}^{S} \pi^{ts} d^t \{v^t(\Phi, z^t) - c^t(\Phi, z^t, x^{ts}) - m^t\} \tag{4}$$

In order to enhance the analytical tractability of the model and to focus on the effects of climate change we will abstract away the stochastic climate parameters given different climate change scenarios. The term ‘a climate change scenario’ here refers to a state, and we do not allow for any stochastic within each of the states.

Instead of starting out with a very general solution to the maximization, we begin with some simple cases. This is done because it enhances the intuition of the authors and hopefully also the readers. The solutions to these simple problems will also serve as benchmarks for the results from analyses of more complex situations.

One particular simplification is that we analyse the choices of the owner in a three-period setting. The choice set of the third period consists of only one element, which we term termination. Throughout the analysis, we will assume that no action is taken at the start of period 3 to prepare for the termination. At the start of the first two periods, the owner first observes the state of the building, then she chooses her action. The different models presented will differ in what types of actions that are contained in the set of possible actions. After the action is chosen the ‘strain-stochastic’ is realized.

Building maintenance and the risks of future climate change

Starting in period 1, strains of the preceding period, and consequently the present state of the building, are observed, and effort is chosen. In period 2, the owner observes the strains and chooses an effort. Within this model the solution to the maximization problem of the owner will consist of a period 1 effort, and a set of efforts for each state in period 2: (m^1, m^{21}, m^{22}, m^{23}, $\cdots$, m^{2S}). For simplicity, the termination value in period 3 is treated as non-stochastic.

$$NV = v^1(\Phi, z^1) - c^1(\Phi, z^1) - m^1 + \sum_{s=1}^{S} \pi^{2s} d^2 \{v^{2s}(\Phi, z^2) \\ - c^{2s}(\Phi, z^2) - m^2 + d^3 T^3 \tag{5}$$

This way of formulating the problem allows us to analyse it using traditional tools of static optimization. Note also that the formulation allows for both the value of the services produced by the building and the operating costs to vary between states. In the first-order conditions in Equations 6 and 7, a definition of a state-dependent survival rate, □^{s}, of the variable component is inserted: $\alpha^s = \frac{\partial z^{2s}}{\partial z^1}$.

$$(\frac{\partial v^1}{\partial z^1}-\frac{\partial c^1}{\partial z^1})\frac{\partial z^1}{\partial m^1}+d^2\sum_{s=1}^{S}\pi^{2s}(\frac{\partial v^{2s}}{\partial z^{2s}}-\frac{\partial c^{2s}}{\partial z^{2s}})\frac{\partial z^1}{\partial m^1}\alpha^s=1 \tag{6}$$

$$(\frac{\partial v^{2s}}{\partial z^{2s}}-\frac{\partial c^{2s}}{\partial z^{2s}})\frac{\partial z^{2s}}{\partial m^2}=1 \qquad s=1,2,3,\cdots,S \tag{7}$$

This gives S + 1 equations determining the S + 1 levels of effort.

In each period 2 states, effort is simply chosen so that the marginal contribution to the net value of the services produced by the building of the last money unit spent on effort equals one. The period 1 condition has a similar interpretation. However, the return of effort made in period 1 is a probability weighted aggregate over periods and states, i.e. it is the expected marginal contribution.

By solving Equation 7 for $(\frac{\partial v^{2s}}{\partial z^{2s}}-\frac{\partial c^{2s}}{\partial z^{2s}})$ and inserting into Equation 6, one gets another interpretation of how period 1 effort is chosen:

$$(\frac{\partial v^1}{\partial z^1}-\frac{\partial c^1}{\partial z^1})\frac{\partial z^1}{\partial m^1}=1-d^2\sum_{s=1}^{S}\pi^{2s}\frac{\frac{\partial z^1}{\partial m^1}\alpha^s}{\frac{\partial z^{2s}}{\partial m^2}} \tag{6'}$$

The expression $\frac{\frac{\partial z^1}{\partial m^1}\alpha^s}{\frac{\partial z^{2s}}{\partial m^2}}$ is the ratio of the marginal technical efficiency in producing z^2 by the alternative factors m^1 and m^2. Measured at the optimal values of (m^1, m^2) the ratio is state dependent. When the ratio is multiplied by the discounting factor it can be interpreted as an economic marginal efficiency, it captures both the technical efficiency and the fact that discounting makes the price of effort made early (in period 1) more expensive than effort made later (i.e. in period 2).

Effort in period 1 is increasing in the expected economic efficiency of m^1 in producing z^2. Hence, it is increasing in the expected survival rate of investments in z made in period 1 and in the discounting factor. This implies that period 1 effort is decreasing in the interest rate used in the discounting. Note that $d^2 = (1 + i)^{-1}$, where i is the relevant interest rate.

The relation between first and second period effort at optimum depends strongly on the substitutability pattern between z^1 and m^2 in the g^s-functions. Two stylized assumptions can be made:

(1) The 'period 2-state *s*' marginal product of effort (at optimum) depends on the levels z^{2s}, irrespective of the amount of effort undertaken in 'state s of period 2'.

(2) The 'period 2-state *s*' marginal product of effort (in optimum) depends on the amount of effort undertaken in 'state *s* of period 2', and not on how much of the factor z is brought forward from the first period.

To see the substantial content of these technical assumptions consider one high and one low period 1 level of z: (z^{1L}, z^{1H}). These levels taken forward to any state in period 2 yield alternative starting values of z: $(\alpha^s z^{1L}, \alpha^s z^{1H})$. By starting values it is simply meant the z^{2s}, that will prevail for $m^{2s} = 0$.

Define $m^{2\#}$ as the effort needed to increase the level of z^{2s} from $\alpha^s z^{1L}$ to $\alpha^s z^{1H}$.

$$z^{2s} = \alpha^s z^{1H} = g^s(\alpha^s z^{1L}, m^{2\#})$$

Then consider a $\hat{z}^{2s} > \alpha^s z^{1H}$, and let $m^{2\#\#}$ be the effort needed to increase the level of z^{2s} from $\alpha^s z^{1H}$ to $\hat{z}^{2s}$.

Under assumption (1), the costs of increasing the level of z^{2s} from $\alpha^s z^{1L}$ to $\hat{z}^{2s}$ will be equal to the sum $m^{2\#} + m^{2\#\#}$. Hence, the marginal efficiency of m^{2s} is, at optimum, independent of the starting values.

When the period 2 choice of effort is analysed and described, the distinction between (1) and (2) is not very interesting. Both of them produce a concave relation between effort and z^{2s}. The effect of period 1 effort on the period 2 choices does, however, differ strongly between these two cases. In case two, the effort made in period 1 does not only determine the amount of z that is brought forward from period 1 to period 2, but also the production technology of period 2. We proceed the paper using assumption (1).

The optimal state of the building in each state in period 2 will, under assumption (1), be independent of the state of the building in period 1, and consequently of effort in period 1. The optimal state of the building in period 2, however, will affect the effort of period 1. The optimal effort in period 1 will exceed the effort made under a myopic optimization in period 1.

Think of a regional-level climate change scenario with higher probabilities for states with a harsh climate. Furthermore, assume that the survival rate of z is lower under harsh climates. Then the expected technical and economic efficiency of period 1 effort (m^1) in producing z^2 will shift down as a response to climate uncertainty. Consequently, period 1 effort will be reduced as a result of (increased) uncertainty in the regional-level climate change scenarios.

How can these algebraic exercises be used to define and say something about the building economics of climate change? First, we have to define a general approach to potential impacts of climate change on the building stock: Let $s = h$ represent the same climate in period 2 as the climate that prevailed in period 1. The difference between the net present value of the building under a constant climate and under climate uncertainty D^a is:

$$\begin{aligned}\mathrm{D}^a &= E(NV^c) - NV \\ &= \{v^1(\Phi, \hat{z}^1) - c^1(\Phi, \hat{z}^1) - \hat{m}^1 \\ &\quad + \sum_{s=1}^{S} \pi^{2s} d^2 \{v^{2s}(\Phi, \hat{z}^{2s}) - c^{2s}(\Phi, \hat{z}^{2s}) - \hat{m}^{2s} + d^3 T^3\} \\ &\quad - v^1(\Phi, \tilde{z}^1) - c^1(\Phi, \tilde{z}^1) - \tilde{m}^1 \\ &\quad + d^2 \{v^{2h}(\Phi, \tilde{z}^2) - c^{2h}(\Phi, \tilde{z}^2) - \tilde{m}^2 + d^3 T^3\end{aligned} \tag{8}$$

Variables with a hat (as $\hat{z}$) are the optimal values of the variables under a particular climate change scenario, and variables with a tilde (as $\tilde{z}$) are optimal values under a given set of historic weather data.

The cost consists of changed performance of the building enclosure, changed operating costs and of changed effort. Note that changed performance in period 1 as a result of the effect a given climate change scenario has on period 1 effort, enters the cost of climate change. In this paper, we will not go any further into discussions of the expressions for the cost of climate change on future building maintenance and operation. Anyway, the purpose of including Equation 8 is two-fold: firstly it is an illustration of which kind of results that can be derived from the model; and secondly, it shows that the cost of climate change is not only determined by the interaction between climatic impact and the technical state of a building. It is also affected by the possible implications of climate change on the behaviour of the decision makers. Behaviour, in this context, should be interpreted as strategies for adaptation.

To illustrate the second point made above: The BRE study (Graves and Phillipson, 2000) is important in so far as it represents an attempt to handle the technical implications of climate change on the built environment. However, their approaches can be seen as a measurement of the expected impacts and costs, given that the decision makers do not adapt. It can be shown that estimates like this can be interpreted as an upper bound for the expected impact or cost of climate change. A more constructive, or political, interpretation is that it is a warning of what might happen if nothing is done.

The model analysed above is somewhat restricted. The only option open to the owner of the building is to continue the use of it. The performance of the building enclosure, and the operating costs, are affected by the effort put into maintenance.

Conversions, scrapping and climate change

General approach

A more realistic approach is to allow for additional elements in the action sets. In addition to maintaining the building, we will here introduce two more possible actions. First, the building can be abandoned or scrapped, either in the first or in the second period. If a building is not scrapped during one of the two first periods, it will be terminated in period 3. We will also allow for conversions of the buildings. By a conversion we mean an action, which alters the fixed component (Φ) in the description of the building.

To handle this analytically, some new symbols need to be defined:

- T^1 is the termination value of period 1;
- T^{2s} is the termination value of state s in period 2;
- $\hat{\Phi}$ is the starting value of the fixed part of the building; and
- $C(\hat{\Phi},\Phi)$ is the cost of converting the fixed part of the building from $\hat{\Phi}$ to Φ.

In the optimization problem that arises out of this, the optimal period 2 reaction to information that arrives in period 2 enters the period 1 decision problem. Furthermore, this choice involves choosing between discrete alternatives. Consequently standard static optimization tools are not suitable, and the problem should be analysed using backward induction.

Instead of spelling out the whole optimization problem, we start by characterizing the choices made in period 2. There are three possible actions in period 2. Start by defining some subsets of the state space S:

- S^{Ci} is the state space consisting of all states where the optimal choice will be to convert the building, given that an ex ante optimally designed strategy i is chosen in period 1, $i = M, C$.
- S^{Ti} is the state space consisting of all states where the optimal choice will be to terminate the building, given that an ex ante optimally designed strategy i is chosen in period 1, $i = M, C$.
- S^{Mi} is the state space consisting of all states where the optimal choice will be to keep the building without any conversions, given that an *ex ante* optimally designed strategy i is chosen in period 1, $i = M, C$.

The state dependent optimal values of the building under each of the three possible actions are given in Equations 9a–c:

$$V^{2s}(C) = v^{2s}(\Phi^2, z^2) - c^{2s}(\Phi^2, z^2) - C(\Phi, \Phi^2) + \frac{d^3}{d^2} T^3 \quad \text{all } s \in S^{Ci} \tag{9a}$$

For simplicity, we include maintenance in the conversion cost function whenever a conversion takes place.

$$V^{2s}(M) = v^{2s}(\Phi, z^2) - c^{2s}(\Phi, z^2) - m^2 + \frac{d^3}{d^2}T^3 \quad \text{all } s \in S^{Mi} \tag{9b}$$

$$V^{2s}(T)=T^{2s} \qquad \text{all } s \in S^{Ti} \tag{9c}$$

The V^2-functions above are a kind of indirect utility functions and their values depend on the z and Φ values that are chosen in period 1. The choice of action in period 2 can be seen as a three-step procedure. First, the state of period 2 is observed. Next, the optimal effort under the M-strategy and the conversion activity under the C-strategy are calculated. In the last step, the value of the building under each of the three strategies are compared, and the strategy yielding the highest value is chosen.

Similarly, the owner has three different possible actions in period 1. The object function for period 1 choice will be somewhat more complex than the object functions for period 2. There are two reasons for this:

(1) When the choices of period 1 are made, the future impact of climate change on building enclosure performance is not known. The value of the building under each of the possible actions in period 2 is affected by the choices of period 1.

(2) The choices of period 1 will partly determine which actions are optimal in period 2. Hence the sets S^{Mi}, S^{Ti} and S^{Ci} are affected by choices made in period 1.

The period 1 value of the building under each of the strategies can be written as Equations 10a–c. The value of the building (NV^1) in period 1 is given in Equation 10d.

$$\begin{aligned} NV(M) = {} & v^1(\hat{\Phi}, z^1) - c^1(\hat{\Phi}, z^1) - m^1 \\ & + \sum_{s\in S^{CM}} \pi^{2s} d^2 V^{2s}(C) \\ & + \sum_{s\in S^{MM}} \pi^{2s} d^2 V^{2s}(M) + \sum_{s\in S^{TM}} \pi^{2s} d^2 T^{2s} \end{aligned} \tag{10a}$$

$$\begin{aligned} NV(C) = {} & v^1(\Phi, z^1) - c^1(\Phi, z^1) - C(\hat{\Phi}, \Phi) \\ & + \sum_{s\in S^{CC}} \pi^{2s} d^2 V^{2s}(C) + \sum_{s\in S^{MC}} \pi^{2s} d^2 V^{2s}(M) \\ & + \sum_{s\in S^{TC}} \pi^{2s} d^2 T^{2s} \end{aligned} \tag{10b}$$

$$NV(T) = T^1 \tag{10c}$$

$$NV^1 = \max(NV(T), NV(C), NV(M)) \tag{10d}$$

Equations 9a–10c constitute a complex dynamic stochastic optimization problem. Instead of spelling out complete and general solutions to this optimization we will characterize some important properties of the solution.

The paper is primarily addressing the uncertainty of future climate affects and the behaviour of owners of buildings. For this reason, the analysis in the remaining parts will focus on the choices made in the first period of the model. Period 2 choices are treated as they are nested within the period 1 choices.

The maintenance strategy

Previously in the paper we analysed the choice of effort (m) in the case where no conversions and no termination took place in the first two periods. The conclusion from this analysis is altered when taking into consideration that the owner knows that for some climate change scenarios she will terminate the building and for other scenarios, she will choose to rehabilitate or convert the building.

The first order condition for the choice of effort in this more general case will be:

$$\left(\frac{\partial v^1}{\partial z^1} - \frac{\partial c^1}{\partial z^1}\right)\frac{\partial z^1}{\partial m^1} + d^2 \sum_{s\in S^M} \pi^{2s}\left(\frac{\partial v^{2s}}{\partial z^{2s}} - \frac{\partial c^{2s}}{\partial z^{2s}}\right)\frac{\partial z^1}{\partial m^1}\alpha^s = 1 \tag{11}$$

As long as the sets S^C and S^T are non-empty, the expected marginal return on period 1 effort, for any level of m^1, is lower than it is when conversions and ‘early scrapping’ is not a part of the action set. Hence, in the presence of climate uncertainty a lower level of effort is put into the maintenance of a building.

Furthermore, the probability of scrapping the building or converting it in period 2 will be higher if a given climate change scenario was anticipated than if it comes as a surprise. If the climate change scenario is not anticipated, the effort in period 1 will be chosen without taking the possibility of scrapping or conversion in order to adapt to a changed climate into consideration. Consequently, a higher level of effort is chosen, and the state of the building, measured by z, will be better than if effort is chosen according to Equation 11. This will increase the value of $V^2(M)$ for any s. As a result, for some s where $V^2(C)$ or $V^2(T)$ gives the maximum of ($V^2(C)$, $V^2(T)$, $V^2(M)$) when m^1 is chosen according to Equation 11, $V^2(M)$ will give the maximum when the owner did not take climate change into consideration.

In order to enhance the understanding of the consequences of choosing the M-strategy in period 1, Equation 10a is rewritten.

$$0 = \sum_{s\in S^{CM}} \pi^{2s} d^2 V^{2s}(M) + \sum_{s\in S^{TM}} \pi^{2s} d^2 V^{2s}(M) \\ -\left(\sum_{s\in S^{CM}} \pi^{2s} d^2 V^{2s}(M) + \sum_{s\in S^{TM}} \pi^{2s} d^2 V^{2s}(M)\right)$$

is inserted into Equation 10a and the expression is rearranged:

$$\begin{aligned} NV(M) = {} & v^1(\hat{\Phi}, z^1) - c^1(\hat{\Phi}, z^1) - m^1 \\ & + \sum_{s\in S} \pi^{2s} d^2 V^{2s}(M) \\ & + \sum_{s\in S^{CM}} \pi^{2s} d^2 \{V^{2s}(C) - V^{2s}(M)\} \\ & + \sum_{s\in S^{TM}} \pi^{2s} \{d^2 T^{2s} - V^{2s}(M)\} \end{aligned} \tag{12}$$

Into this expression, some definitions are inserted:

$$\Gamma^C = \sum_{s\in S^{CM}} \pi^{2s} d^2 \{V^{2s}(C) - V^{2s}(M)\}$$

$$\Gamma^T = \sum_{s\in S^{TM}} \pi^{2s} \{d^2 T^{2s} - V^{2s}(M)\}$$

The symbols Γ^C and Γ^T are the expected values of the possibility to choose the strategy in period 2 whenever this is advantageous. Hence, they are real option values. The definitions of S^{CM} and S^{TM} ensure that these are positively signed. Their size depends, among other things, on the level of effort put into maintenance.

$$\begin{aligned} N^V(M) = {} & v^1(\hat{\Phi}, z^1) - c^1(\hat{\Phi}, z^1) - m^1 \\ & + \sum_{s\in S} \pi^{2s} d^2 V^{2s}(M) + \Gamma^C + \Gamma^T \end{aligned} \tag{12b}$$

Using these definitions, one find that the (expected) value of a building, which in period 1 is optimally maintained, can be expressed as the sum of four components:

- the net value of the building in use in the first period;
- the expected value of the building in period 2, aggregated over all possible states, if it is optimally maintained;
- the value of the real option to convert the building if this is profitable when the future climate conditions are observed; and
- the value of the real option to scrap the building if this is profitable when the future climate conditions are observed.

The normal action taken by an owner of a building is to maintain it in a suitable way. The decision to convert or to scrap is a more drastic, and less frequent, decision. In the remaining parts of the paper, the choice of the maintenance strategy will be termed 'continued ordinary use'.

This apparatus can be used for an informal characterization of the result on the mutual dependency between the maintenance efforts made in period 1 and the conversion and scrapping probabilities, referred above: Up to a certain point the net value of the building in use in the first period is increasing in m^1. The period 2 value of the building if it is not scrapped or converted is increasing in m^1, because this, in every state, increases the state of the building as measured by z. The value of the real options, and the probability that they will be exercised, will however be decreasing in m^1. Hence, there is a trade-off between actions that enhance the value of the building in continued ordinary use and actions that enhance the value of the possibility to adapt the building to changed future weather conditions.

The uncertain risks of future climate change can be interpreted as a situation where probabilities of states where conversion activities and scrapping take place are higher than they are under a steady state. Under this interpretation, one can say that increased climate uncertainty implies that owners will give more weight to actions that increase the value of the possibilities to utilize future climate information. From the arguments above, it is seen that this means that effort put into maintenance prior to the realization of a given climate change scenario is decreasing due to the uncertainty related to the likely range and nature of future weather scenarios.

The conversion strategy

The value of an optimally designed conversion strategy in period 1 can be written as the sum of the value of the building in 'continued ordinary use' and the value of the real options associated with conversion or scrapping. The reformulation of the expression for *NV*(*C*) is done the same way that *NV*(*M*) was reformulated in Equation 12:

$$\begin{aligned} NV(C) = {} & v^1(\Phi, z^1) - c^1(\Phi, z^1) - C(\hat{\Phi}, \Phi) \\ & + \sum_{s\in S} \pi^{2s} d^2 V^{2s}(M) + \Omega^C + \Omega^T \end{aligned} \tag{13}$$

Where the real options are:

$$\Omega^C = \sum_{s\in S^{CC}} \pi^{2s} d^2 \{V^{2s}(C) - V^{2s}(M)\}$$

$$\Omega^T = \sum_{s\in S^{TC}} \pi^{2s} d^2 \{T^{2s} - V^{2s}(M)\}$$

Some remarks on the conversion technology can be given. At the start of period 1, the clay-factor has a value $\hat{\Phi}$. Then consider two alternative values $\hat{\Phi} < \Phi^a < \Phi^b$. Define

$$C(\hat{\Phi}, \Phi^b) = C(\hat{\Phi}, \Phi^a) + d^2 C(\Phi^a, \Phi^b) + K \tag{14}$$

where $K < 0$, as a normal conversion cost structure. Hence, it is more expensive to make a two-step conversion than to do all the conversions in one single step. Such a structure will arise if there are fixed costs associated with starting up a conversion project. Assume $K = 0$, and that a conversion is considered in period 1. Consider the states where a conversion is profitable in period 2. As long as $K = 0$ this can be done without incurring new fixed conversion costs. A conversion today will not reduce the profitability of future conversions. To put the argument the other way around: as long as there is sufficient economies of scale in undertaking a conversion ($K < 0$), the uncertainty could make it profitable to postpone a conversion until one learns more about the range and nature of climatic impacts of the future.

In addition, the existence of states where the building will be scrapped (in period 2) will reduce the profitability of period 1 conversion. The presence of economies of scale in conversions and/or possible future climates (or states), where a building will be scrapped, leads to a (partial) decrease in the propensity to undertake conversion activities.

Some short remarks on the scrapping strategy

In a myopic framework, the scrapping criterion is quite simple. If the net value of the building in use exceeds the termination value it should not be scrapped. The termination value will typically equal the value of the lot in alternative use minus demolition costs. The difference between the net value in use and the termination value can be termed a quasi-rent. Alfred Marshall introduced the concept of the quasi rent, in order to distinguish between the rent on produced capital in the long and the short run (Førsund, 1984). Note that a positive quasi rent suffices for inducing the owner to keep her building in use. To induce an owner to set up a new building a rent that also yields (at least) a normal return on invested capital is needed.

In a dynamic setting with different possible climate regimes, the quasi rent criterion gets a little more complex. Under such a framework, it must be taken into account that scrapping today kills the option to scrap, or convert, tomorrow. This value can be positive partly because future lot values are uncertain, and can consequently increase the value of ‘continued ordinary use’ of the building. Consequently, the uncertainty of climate change can reduce the amount of buildings that are scrapped in period 1. In our simple three-period model, this will lead to an increased scrapping activity in period 2.

Empirical studies of how the quasi rents in different vintages of the building stock are affected under different climate change scenarios could provide important insight into the climate vulnerability of a society (see Førsund, 1981).

Further work

This paper is embedded within the ongoing NBI Research & Development Programme ‘Climate 2000’ (Lisø and Kvande, 2004). Our ambition is to use the theoretical apparatus developed here as a tool for empirical analysis of potential implications of climate change on the building stock and on the behaviour of decision makers. A narrow-minded technical approach to this question could be to measure and predict the climatic strains that hit the building stock and evaluate how this affects the state and performance of buildings and building enclosures.

However, stakeholders react towards information on changed climatic strains hitting the building stock, and they adapt. The framework of this paper should help to understand these adaptations, the interdependencies between them, and the effects on the state and performance of buildings. At later stages of the project, we will characterize different vintages and classes of the building stock according to which kind of adaptation one should expect using these tools. Camilleri *et al.* (2001) stress that their research on impacts of climate change on building performance in New Zealand shows large differences between classes of buildings and locations. This calls for an approach where impact studies treat a diversity of classes and vintages of buildings, and take their heterogeneity into consideration.

Operation and use of a building involves a multiplicity of stakeholders. In our model, this is simplified down to one single agent – the owner. In reality owners, tenants and insurance companies share the responsibility of the climatic strains that a building is exposed to. In effect, there exists co-ordination problems arising out of the fact that some costs of adaptations are borne by some of the agents, while the gain of them are collected by others: Why shall I prepare my roof for a potentially more severe climate if the insurance covers a collapse?

We find it especially important to investigate the role of insurance. How will the menu of insurance contracts be affected by climate change? What about their price? Will increased risks be pooled or should one expect higher occurrences of separating insurance contracts (see Rothschild and Stiglitz, 1976)? Questions like this could, and should, be treated within behaviour models of the type presented in this paper. Changed conduct by insurance companies will change the conduct of other stakeholders, probably in a way that reduces the adverse impacts of climate change in the built environment. Hence, a more efficient risk sharing can reduce aggregate risk exposure.

The focus on insurance leads us to another feature not treated in this paper: Damage to buildings. The best way to incorporate building damage into the model is probably to allow for stochastic damages. The probability of damages occurring will vary between different climate change scenarios, and with actions taken by the owner: For example through the choice of the fixed component, Φ. In principle, the model can handle a multiplicity of damages.

The 'robustness' of the Norwegian building stock will also be addressed as part of the programme. One important area of investigation will be the development of methods for classifying different climatic parameters and their impact on building enclosure performance. The work will include the preparation of a thorough overview of the relevant climate variables that should be taken into account during the planning, design and construction of building enclosures in various parts of Norway. This work will create a basis for further development of our analytical framework.

It is preferable to analyse the effect of climate uncertainty under a multi-period setting where information on climate change under global warming evolve over time. Some of our conclusions will probably be altered under an infinite time horizon. Qualitatively the conclusions will hold. What we get under our three-period setting is a stylized picture of the first part of a path of effects. In addition, under a longer time-horizon, the real options will exist.

One simple way to start an empirical analysis of the factors analysed here is to single out one class of buildings that are heavily exposed to certain impacts of climate change and analyse maintenance and conversion activities undertaken in these buildings. Possible candidates for such an investigation are buildings that are exposed to increased probabilities of precipitation, flooding or extreme wind loads.

Concluding remarks

In this paper, we have developed a highly stylized and abstract model of the decisions of a building owner facing an uncertain evolvement of the climate. A non-sympathetic reading of the paper will lead to a question of whether it only consists of an endless row of manipulations of symbols leading nowhere. This is not our conclusion. On the contrary, we believe that the model describes important aspects of the decisions that are taken, and that it identifies the determinants of the decisions. As discussed in the paragraph on further work there is still a lot of theoretical work to be done in analysing these structures. However, even at this early stage hypotheses for empirical work can be extracted.

The model shows that the decisions are affected by both the expected profitability of the different actions and the effects the actions have on the profitability of future choices. Hence, using a real option approach enhances our understanding of actions taken by owners of buildings. Some simple results are derived. Climate change can reduce both conversion activities and the occurrence of scrapping of buildings. Hence, future climate uncertainty can increase the economic lifetime of a building. Furthermore, given that a building is 'continued in ordinary use', less effort will be put into maintenance. It is also argued that measures of the building related costs of different impacts of climate change on building enclosure performance should be based on an analysis of expected adaptation measures.

Throughout the paper, we have discussed the interdependencies between potential implications of climate change and the behaviour of building owners. The model has a wider applicability. Structures and mechanisms discussed are also relevant for other parts of the built environment. Even though much substance is extracted from the analysis, we point towards important adaptations and extensions of the analytical apparatus that calls for further research. Hence, this paper can really be said to be a primer. We find it of significant importance to put effort into production of a coat of primer before putting on the main paint.

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Integrated approach to risk management of future climate change impacts

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The vulnerability of the built environment will be influenced by global-scale climate change. However, there are large uncertainties associated with the future performance of buildings due to changes in regional- and local-scale climatic impact. The use of modern risk-management theories is discussed for developing cross-disciplinary strategies to meet the challenges of future climate change. It is shown that there are benefits to be gained from the introduction of risk-management strategies within a greater extent of the construction industry. Cross-disciplinary risk-based management strategies (ensuring cooperation along vertical decision-making lines), together with design guidelines that account for both historical local climatic conditions and scenarios for future changes, can be an important step towards a more active and dynamic way of ensuring a high-quality construction process and a sustainable built environment. Reducing the potential for defects or damage through the development of technical and organizational preventive measures (a risk-based management strategy) while at the same time applying the precautionary principle and discursive strategies in the design, construction and geographical localization of buildings, is likely to increase the robustness of the built environment in the light of the unknown risks of future climate change.

Keywords: adaptation, adaptive capacity, building stock, climate change, global warming, risk management, robustness, vulnerability, Norway

La vulnérabilité du milieu bâti va subir l'influence des changements climatiques à l'échelle du globe. Il reste toutefois de grandes zones d'incertitude associées aux futures performances des bâtiments du fait de l'impact variable des changements climatiques à l'échelle régionale et locale. L'auteur examine le recours aux théories modernes de gestion des risques afin de formuler des stratégies interdisciplinaires capables de relever les défis que posent les futurs changements climatiques. Il apparaît qu'une grande partie de l'industrie du bâtiment pourrait bénéficier de l'introduction de stratégies de gestion des risques. Ces stratégies interdisciplinaires (qui favorisent la coopération le long de processus décisionnels verticaux) ainsi que les lignes directrices qui tiennent compte à la fois des conditions climatiques locales historiques et de scénarios qui intègrent les changements à venir, peuvent constituer une étape importante vers une manière plus active et plus dynamique d'assurer un processus de construction de haute qualité et un milieu bâti durable. La réduction des risques de défauts ou d'endommagement par la mise en œuvre de mesures préventives sur les plans technique et organisationnel (une stratégie de gestion basée sur les risques), l'application du principe de précaution et des stratégies discursives sur la conception, la construction et la localisation géographique des bâtiments vont vraisemblablement améliorer la robustesse du milieu bâti à la lumière des risques inconnus posés par les futurs changements climatiques.

Mots clés: adaptation, capacité d'adaptation, parc immobilier, changement climatique, réchauffement global, gestion des risques, robustesse, vulnérabilité, Norvège

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Introduction

At present, building design codes, standards and operational procedures are based on historic weather data. The existing building stock in the next few decades is likely to be exposed to significantly different climatic strains compared with today due to climate change.

> We are venturing into the unknown with climate, and its associated impacts could be quite disruptive.
>
> (Karl and Trenberth, 2003, p. 1719)

The present paper discusses the use of modern risk-management theories as a basis for the development of cross-disciplinary strategies to meet the challenges of future climate change within the built environment. First, climate vulnerability and adaptation are discussed in general. Next, a point of departure for the support of decision-making aimed at reducing climate vulnerability in the built environment is suggested using established risk-management strategies and Norway as a starting point. Finally, possible ways of supporting decision-making aimed at ensuring sustainable buildings are suggested by applying a flexible combination of risk-based, precautionary and discursive risk-management strategies.

Climate change

Modern climate change is now dominated by human influences large enough to be compared with the bounds of natural variability, the main source of global climate change being human-induced changes in atmospheric composition (Karl and Trenberth, 2003). Man-induced climate change can be avoided in the long-term only by reducing global emissions of greenhouse gases to a fraction of present levels within one or two centuries (Hasselmann *et al.*, 2003). Regional changes in climate, particularly increases in temperature, have already affected several physical and biological systems in many parts of the world, e.g. the shrinkage of glaciers, the thawing of the permafrost, and the lengthening of mid- to high-latitude growing seasons (McCarthy *et al.*, 2001). Measures aimed at halting global climate change through greenhouse gas mitigation options need to overcome many technical, economic, political, cultural, social, behavioural and/or institutional barriers that prevent the full exploitation of the technical, economic and social opportunities of these mitigation options (Metz *et al.*, 2001).

The possible effects of climate change, and the subject of risk management, adaptation and mitigation, are now being addressed in several parts of the world. Challenges confronting the built environment in responding to the potential impacts of climate change were one of the main themes in a special issue of *Building Research &Information* (**31**[3–4]; 2003) (Du Plessis *et al.*, 2003; Hertin *et al.*, 2003; Larsson, 2003; Lisø *et al.*, 2003; Mills, 2003; Sanders and Phillipson, 2003; Shimoda, 2003; Steemers, 2003). An overview of Norwegian climate policies, climate change scenarios, potential impacts (including impacts on building performance) and practical implications of preparing Norway for climate change is presented by Lisø *et al.* (2003) and O'Brien *et al.* (2004). Another special issue of *Building Research &Information* (**32**[5]; 2004) presents new research on managing risks from natural hazards (Comerio, 2004; Spence, 2004; Spence and Kelman, 2004; White, 2004).

Norway's climate is extremely varied, the rugged topography being one of the main reasons for large local differences in temperature, precipitation and wind speed over short distances. The country's long coastline and steep topography make it particularly prone to extreme events such as coastal storms, avalanches and landslides. Regional scenarios for climate change over the next 50 years in Norway indicate an increased risk from extreme weather. Together with a warmer climate, especially during the winter, an increased risk for intense precipitation over parts of coastal Norway and more frequent incidents of strong winds along the coast of the two northernmost counties and off the coast are estimated. These scenarios, emanating from the project 'Regional Climate Development Under Global Warming (RegClim)',[1] are downscaled from a global climate model run by the Max-Planck Institute for Meteorology in Hamburg, Germany. There are several sources of uncertainties related to both scenarios for global climate change and to the effects of global warming on regional-level climate. The regional scenarios should not be considered as 'forecasts', but rather as an indication on the likely range and nature of future weather scenarios (Lisø *et al.*, 2003).

Climate vulnerability and adaptive capacity

Key challenges

Norway's vulnerability is likely to be influenced by impacts from global-scale climate change, even though the country is considered to have a high adaptive capacity based on macro-level indicators such as wealth, technology, information, skills, infrastructure, institutions, equity, empowerment and the ability to spread risk (McCarthy *et al.*, 2001; Yohe and Tol, 2002; O'Brien *et al.*, 2004). However, few studies have demonstrated that these factors will actually lead to successful adaptation in Norway (Lisø *et al.*, 2003). Regional- and local-level assessments indicate that climate change will entail considerable challenges to some regions and social groups (O'Brien *et al.*, 2004). Investigations carried out by the Norwegian Building Research Institute (NBI) indicate that the cost of repairing process-induced building defects in Norway amounts to 5% of the annual capital invested in new buildings (Ingvaldsen, 1994). Ingvaldsen also found that this estimate was in good agreement with 13 corresponding investigations or sources of information in other European countries (with a mean estimate varying between 3 and 5%). Correcting faults and repairing defects in buildings during the construction process is estimated to cost roughly the same as repairing buildings in use, e.g. another 5% (Ingvaldsen, 1994). With an annual investment in refurbishment and new construction of 130 billion Norwegian kronor (as of 2003), it is therefore reasonable to estimate that up to 13 billion kronor is being spent on repairing defects or damage to buildings every year.

NBI has more than 5000 process-induced building defect assignment reports in its archives, which is a considerable source of experience-based knowledge. Results from a preliminary review of assignments investigated in the decade between 1993 and 2002 (2378 building defect cases registered and described in 2045 assignment reports) show that defects related to the building envelope constitute about two-thirds of the investigated cases (Lisø *et al.*, 2005a, b). Moisture as the main source causing the defect accounts for as much as 76% of all investigated cases in that decade. Many types of building defect cases are recurring items, which indicates a general lack of knowledge amongst the different actors in the construction industry concerning fundamental principles of building physics. These findings support earlier investigations concluding that the construction industry is unable to learn from past experience and that the exchange of knowledge in construction projects is unsatisfactory (e.g. Lisø *et al.*, 2000).

A field investigation of a random sample of 20 existing low-rise buildings with large spans (e.g. schools, sports buildings and industrial buildings) situated in areas exposed to high wind action and extreme snowfall in Norway shows that 18 of these buildings do not meet current regulatory requirements relating to safety against collapse owing to snow loads and wind action (Meløysund *et al.*, accepted).

Projected changes in climatic conditions will further enhance vulnerability within the construction industry and the built environment.

Key definitions

At the outset of this paper, it is sensible to clarify a few key definitions to be used in further discussions on risk-management and decision-making instruments.

'Risk' is termed here as a function of the probability of undesirable events and the subsequent consequences of these (Norges offentlige utredninger (NOU), 2000), and in the International Standardisation Organisation (ISO)/IEC Guide No. 73:2002 (ISO, 2002), it is defined as a 'combination of the probability of an event and its consequence'. Risk expresses the potential loss of important values as a consequence of undesirable events, e.g. adverse social, economic and technical implications of climate change in the built environment. Risk-reducing measures or activities are normally assessed with reference to quantitative risk acceptance criteria.

'Risk management' is defined in ISO (2002, p. 4) as 'coordinated activities to direct and control an organization with regard to risk'. Risk management implies that undesirable outcomes can be avoided, but where they are unavoidable, they can be mitigated if connections between cause and effect are properly defined (Jaeger *et al.*, 2001).

'Risk analysis' provides a basis for the evaluation of risk and is defined as 'systematic use of information to identify sources (having a potential for a consequence) and to estimate the risk' (ISO, 2002, p. 5). The risk of adverse impacts as a consequence of climate change is not well determined, and the risk-management principle adopted should be the ALARP principle: the risk should be reduced to a level that is 'as low as reasonably practicable'.

The Intergovernmental Panel on Climate Change (IPCC) definitions of sensitivity, adaptability and vulnerability are as follows (McCarthy *et al.*, 2001):

> 'Sensitivity' is the degree to which a system is affected either adversely or beneficially, by climate-related stimuli. Climate-related stimuli encompass all the elements of climate change, including mean climate characteristics, climate variability, and the frequency and magnitude of extremes. The effect may be direct (e.g. a change in crop yield in response to a change in the mean, range or variability of temperature) or indirect (e.g. damages caused by an increase in the frequency of coastal flooding due to sea-level rise).
>
> 'Adaptive capacity' is the ability of a system to adjust to climate change, including climate variability and extremes, to moderate potential damages, to take advantage of opportunities, or to cope with the consequences.
>
> 'Vulnerability' is the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity.

In this context, a system can be the whole built environment, clusters of buildings in a defined geographical area or just a single building. Vulnerability and adaptation are also discussed by Lisø *et al.* (2003). In 1999, the government appointed an official committee to review Norway's social vulnerability and disaster preparedness (NOU, 2000, p. 21). Its report defines vulnerability as follows:

> 'Vulnerability' expresses the problems a system will have functioning when exposed to an undesirable incident, and also the problems the system experience when trying to resume its activities after the occurrence of an undesirable event. Vulnerability is identified with a possible loss of value. The system can in this context be a state, the national power supply, an industry or enterprise or a single computer system. Vulnerability is to a large degree self-inflicted. It is possible to influence the degree of vulnerability, to limit and reduce it.
>
> (translated from Norwegian)

The latter definition is far more general than the IPCC definition, which is limited to the threats of climate change. The NOU definition of vulnerability embraces all problems a system could encounter. However, they are both appropriate starting points for discussions on adaptive measures and strategies.

Bayesian approach

A classical approach to risk and risk analysis requires well-defined data on the probability of occurrence and the extent of impacts. Obviously, this is not the case facing the unknown risks of future climate change. A complementary approach to the risk-based, precautionary and discursive strategies described in this paper could be to employ Bayesian methods. Bayesianism, named after the British mathematician Thomas Bayes (1702–61), is the philosophical principle that the mathematical theory of probability applies to the degree of plausibility of statements, or to the degree-of-belief of rational agents in the truth of statements. The starting point of Bayesian methods is the same as in all risk analysis, as it is assumed that there exists an underlying true risk. This risk is unknown, and subjective probability distributions are used to express uncertainty about where the true value lies (Aven, 2003). That is, a Bayesian approach to risk allows for degree-of-belief interpretations of mathematical probability. The Bayesian approach is a systematic way of combining prior information or belief in a statement and empirical observations. Hence, a Bayesian analysis is a way to use information to update prior beliefs. However, one could assert that all probabilistic arguments in fact are Bayesian, except, of course, in trivial instances such as throwing dice. Projections of future climate risks that were made before global warming was recognized were based on the belief that future climatic impacts would be approximately the same as the past (e.g. as when using historical climate data in the design of buildings).

Aven (2003) provides a thorough description of a predictive approach to Bayesian analysis.

Introducing risk-based management strategies

Institutional capacity

To cope with actual and potential changes in climate and climate variability, it is necessary that affected institutions have the organizational and technological capacity and human resources needed to combat these challenges. The full range of impacts resulting from climate change is still uncertain, but it is becoming increasingly clear that adaptation to climate change is necessary within several sectors (Lisø *et al.*, 2003). Adaptation to severe climate conditions has always been crucial for the viability of Norwegian society. However, both the functionality of the existing built environment and the design of future buildings are likely to be altered, and areas of vulnerability in the construction industry must be identified (e.g. changes in the decay rate of materials and structures due to changes in temperatures and precipitation patterns). These issues need to be considered by all actors (on all levels) involved in the design, construction and geographical localization of buildings, challenging the capacity and cooperative abilities of institutions to effect the necessary adaptation measures.

Government regulatory measures

Ways to strengthen institutional capacity to implement appropriate building performance requirements and standards, and thus reducing the sensitivity of the built environment, is an important element in adaptation to climate change (Lisø *et al.*, 2003). Spence (2004) examines national policies of risk mitigation and states that improved government action and regulation can contribute to the reduction of impacts from natural disasters. The most important government regulatory measure to ensure adherence to building codes and standards is the Technical Regulations under the Norwegian Planning and Building Act, which since 1997 have been performance-based. The principal motive for a transition from a prescriptive code to a performance-based code in Norway was to contribute to an increase in the quality of buildings and a reduction of the amount of building defects. Preliminary findings from a case study of process-induced building defects suggest that the adoption of a performance-based building code has indeed led to a positive change in quality (Mehus *et al.*, 2004). Reviews of the implementation of performance-based codes in New Zealand also show that performance-based codes have advantages if carefully implemented to capture these advantages (Duncan, 2005). Performance-based codes may also have the opposite effect by being more complex and thus more difficult to enforce or easier to evade.

The material rules of the Planning and Building Act and the technical requirements of these Regulations are deemed to be fulfilled if the products employed are in conformity with established requirements on products for construction works and methods and execution are in conformity with Norwegian Standard, equivalent standard or European technical approval. However, the building authorities cannot demand that methods and execution according to Norwegian Standard, equivalent standard or European technical approval be used if the requirements for the construction works are satisfactorily fulfilled in other ways (e.g. documentation through pre-accepted solutions).

The present general trend in legislation and regulation away from prescriptive rules to performance-based codes will increase the need for interaction between regulatory decision-makers and experts within relevant fields or disciplines (Rasmussen, 1997). The transition from a prescriptive to a performance-based code (e.g. functional criteria) implies that the interpretation of the codes is delegated to different actors in the construction industry, and has thus strengthened the demand for supporting standards and design guidelines. The NBI Building Research Design Sheets in the Building Research Series comply with the performance-based requirements in the building code, and are an important reference to pre-accepted solutions. These design sheets could be used as a foundation for precautionary adaptation measures in the construction industry, and would be an excellent starting point for precautionary adaptation measures. However, alterations of regulatory measures and design guidelines within the construction industry constitute only a partial adaptation to climate change. In order to develop necessary adaptation strategies, larger societal and cross-disciplinary adjustments are crucial (Lisø *et al.*, 2003).

Managing risks: principal approaches

Introduction

Klinke and Renn (2001) present an integral risk concept consisting of a criteria-based risk evaluation aimed at an analytic-deliberative approach in risk regulation. Six risk classes, all with names from Greek mythology, are deduced from eight criteria for evaluating risks (damage potential, probability of occurrence, incertitude, ubiquity, persistency, reversibility, delay effect, mobilization potential). These characterizations and classifications of risks provide a well-funded point of departure for the design of risk policies, management strategies and measures for risk reduction associated with potential impacts of climate change on the built environment. One of these risk classes is used by Klinke and Renn (2001, p. 165) to classify the atmospheric greenhouse effect, the risk class 'Pythia', because 'the extent of changes is still not predictable'. The Ancient Greeks consulted their oracles in cases of uncertainty. The sayings of sibyls and oracles were 'notoriously open to interpretation': the oracle at Delphi (commonly known as the Pythia) was no exception.[2] A great danger could threaten, but the probability of occurrence, the extent of the damage, the allocation and the cause of the damage remained uncertain, i.e. both the probability of occurrence and the extent of damage could be intolerable.

Precautionary strategy

The risk class Pythia demands the application of a precautionary risk-management strategy, as uncertainty is attached to both frequency and consequences. In this paper, this risk class will be used to illustrate a point of departure for discussions on risk-management strategies related to climate change and the built environment. The future risk of adverse impacts of climate change on buildings is connected with uncertainty. Thus, the risk potential is characterized by a relatively high degree of uncertainty concerning both probability of occurrence and extent of damage. Precaution in this context means the development of policies on mitigation, adaptation, monitoring and continuous research, even if there is no clear evidence of future harmful impact. Technically, uncertainty concerning the probability of occurrence and the extent of damage can be handled as probability distributions over probability distributions: The probability of a future occurrence of an event is unknown, but one can hypothesize that this probability is in itself a stochastic random variable with a certain distribution. These ideas are discussed by Nordvik and Lisø (2004).

However, as new knowledge leads to a greater understanding of global-, regional- and local-level climate change and associated effects, and thus reduces uncertainty, other risk-management strategies could be advantageous. When the main criteria of risk classification, probability of occurrence and extent of damage, are relatively well known, a risk-based management strategy could also be applied. Reducing the potential for damage through the development of technical and organizational preventive measures (a risk-based management strategy), while at the same time applying the precautionary principle in the design, construction and geographical localization of buildings, is likely to increase the robustness of the built environment.

Many different levels of politicians, authorities and actors in the construction industry are involved in the control of a safe and robust built environment by means of regulation, building codes, guidelines and operational procedures. Rasmussen's (1997) description of the socio-technical system involved in the control of safety provides an excellent illustration of the complexity of risk management in a dynamic society, with a very fast pace of change of information and communication technology, and increasing demands for profit and shorter construction periods. Rasmussen concludes:

> risk management must be modelled by cross-disciplinary studies, considering risk management to be a control problem and serving to represent the control structure involving all levels of society for each particular hazard category. (p. 183)

Cross-disciplinary studies are to be separated from multidisciplinary studies, as in this context it is necessary to ensure cooperation along vertical decision-making lines, i.e. from government regulatory bodies via local regulatory bodies and inhabitants, research communities and company management to the craftsmen on site. The importance of horizontal cooperation on all these levels must, of course, still be highly emphasized.

Discursive strategy

The challenge of adapting to global climate change is especially important for the built environment, having an expected lifetime from 60 to more than 100 years (and far more for cultural heritage buildings). The possible impacts of climate change on the building stock being built over the next few decades must therefore be addressed today. However, present design standards, codes of practice and operational procedures do not take potential climate change impacts into account. A sustainable built environment depends on these questions being sufficiently addressed by all actors in the construction industry. This can only be done if the challenge of climate change is acknowledged amongst the users of the built environment. At present this is not the case (Lisø *et al.*, 2003). A lack of awareness of climate change impacts calls for a third management strategy to be introduced: the discursive strategy. This strategy is both appropriate and necessary where the potential for wide-ranging damage is ignored due to a delay effect as, for example, the impacts of future climate change, i.e. the risk is not being taken seriously because of the delay between the initial event and the damage impact (Klinke and Renn, 2001). Discursive management strategies, however obvious they may appear, are necessary when building awareness and confidence, strengthening regulatory bodies and initiating collective efforts by institutions to take responsibility (the dictionary definition of the word 'discursive' is 'proceeding to a conclusion by reason or argument rather than intuition').

Application of precautionary and discursive risk-management strategies

In the above sections, climate vulnerability, adaptation measures and established risk-management strategies were presented in general. In the following sections, the application of precautionary and discursive risk-management strategies as a means to increase the robustness of the built environment is discussed in more detail.

The building stock some time into the future consists of the building stock of today and of new construction. Parts of the present building stock in the future will be adapted to changes in the environment, while parts are kept as is. Analysis of how the building stock is affected by the risks of future climate change should handle this diversity (Nordvik and Lisø, 2004). A successful implementation of the precautionary principle calls for an understanding and awareness of the potential future risks and a decision model that ensures interaction between all actors in the construction industry, from regulatory bodies at government level to the different actors on the construction site.

The task of preparing the construction industry for the unknown risks associated with future climate change impacts is complex. While some adaptation measures can be undertaken by actors within the industry alone, the importance of addressing the underlying causes and constraints of both sensitivity and coping capacity means these measures must be supplemented by ones that go far beyond the construction industry (Lisø *et al.*, 2003). Today, no holistic or conscious strategy or policy for addressing these 'wider-than-sector' issues exists in Norway. Natural disasters caused by extreme weather events, avalanches, storm surges or landslides are obvious challenges. However, variations over normal everyday impact from different climate parameters in a country with extremely varied climate conditions are also a significant challenge. Climatic impact causes extensive degradation and damage to the built environment every year, e.g. refer to the earlier example on building defects in Norway.

The design of building envelopes should be expected to be the result of choices based on optimally utilized information and knowledge on both building technology and the different impacts to which the buildings are exposed (Nordvik and Lisø, 2004). Several sources of uncertainties exist related to both scenarios for global climate change, and to the effects of global warming on regional- and local-level climate in different parts of the country. However, an increased focus on the impacts of different climatic parameters on building envelope performance will lead to a more climate-adapted design in new construction, and also to a more robust performance of existing buildings.

The potential benefits or adverse implications of climate change on the building stock can be addressed at different levels (Nordvik and Lisø, 2004):

- How will the performance and cost of operating of existing buildings be affected by climate change if the buildings are kept unaltered?
- How should existing buildings be adapted to changes in climatic impact? At what costs can this be done, and when should it be done?
- How will the technical and economical lifetime of buildings be affected by climate change?
- How will the choice of technology, materials and design in new construction be affected?
- How will the time path of the level of new construction be affected?

Nordvik and Lisø (2004) use tools from economic theory to develop a stylized and abstract model of the decisions of a building owner facing an uncertain evolution of the climate. This is done through the use of a putty-clay model (i.e. building characteristics can only be changed through major economic efforts such as retrofitting or alterations once they are erected). Using the real options approach to building economics, it is found that uncertainty about which climate regimes will prevail in the future enhances the profitability of actions which increases future flexibility. The real options approach starts from the fact that choices today affect (and sometimes determine) the set of future choice alternatives and their profitability. Hence, a positively valued real option may be a part of the pay-off of an immediate action. This is related to the precautionary principle as it explicitly treats the link between present choices and future possibilities – or options. It is argued that uncertainties related to potential impacts of future climate change in fact can reduce maintenance, reconstruction and the occurrence of scrapping of buildings. Hence, future climate uncertainty can in fact increase the economic lifetime of a building. This example illustrates the complexity of the challenge at hand.

Efforts made to increase the robustness and sustainability of the built environment must be addressed both at the regulatory and the operative levels. The latter requires the introduction of risk-management models that focus on the behaviour psychology of the different actors in the construction process. The reaction of individuals to external influences is of major importance when addressing risk management and climate change, which is a vast topic that clearly needs more research. Rasmussen (1997) states that the behaviour of a dynamic socio-technical system (i.e. the built environment) cannot be represented in terms of task sequences and errors, referring to a 'correct' or 'rational' performance. Furthermore, he concludes that task analysis focused on action sequences and occasional deviation in terms of human errors should be replaced by a model of behaviour-shaping mechanisms in terms of work system constraints, boundaries of acceptable performance and subjective criteria guiding adaptation to change. This approach, based on multidisciplinary research on industrial risk management, might also be beneficial for the development of adaptation strategies to meet the unknown risks of future climate change.

Raising awareness of climate change: a key discursive strategy

The ways in which the construction industry interacts with other sectors (as well as interactions between political, social and economic processes at large) clearly needs further understanding. The Norwegian government has regulated the insurance market by establishing a risk-pooling mechanism in the case of natural perils, including climatically triggered extreme events. Although the Norwegian Pool of Natural Perils addresses collective security and insurance, no climate change-related measures exist that target the underlying causes of sensitivity and coping capacity, or any of the factors constraining institutional capacity to effectuate adaptation (Lisø *et al.*, 2003). Factors that need to be considered are, for example, institutional fit, the interaction between institutions, goal conflicts and power relations, government incentive structures, competing concerns within institutions (Næss, 2002), and the responsibility of the academic teaching environment.

The Norwegian University of Science and Technology (NTNU) and NBI envisages the development of a field of expertise in which wide-ranging knowledge about meteorology, climatology, atmospheric science, architecture (building practice) and construction technology is carefully integrated, and it aims to ensure the construction of reliable, climate-adapted buildings and built environments in the future. The challenge of future climate change necessitates academic institutions with long-term strategies on the education of engineers and architects. Raising awareness of this challenge not only make would the actors in the construction industry able to reduce adverse impacts of climate change, but also would lead to a better understanding of the need for local climate adaptation of buildings and other infrastructure.

Independent institutions with high social esteem are important brokers for informing the public about the results of scientific research (Klinke and Renn, 2001). The Technical Regulations under the Norwegian Planning and Building Act are performance based, which necessitate supporting standards, design guidelines and pre-accepted solutions. NBI, as an independent institution developing technical guidelines (the Building Research Design Sheets) that reach out to almost all actors in the Norwegian construction industry, thus has an important role in the development of precautionary and discursive management strategies aimed at building awareness of the future risks of climate change and initiating collective efforts by regulatory bodies and other institutions to take responsibility. The institute provides guidelines, solutions and recommendations that comply with the building code and that encourage high quality in the planning, design and construction of buildings. It is by far the most used planning and design tool amongst Norwegian architects and engineers.

In Norway, the Directorate for Civil Protection and Emergency Planning was established in September 2003 (under the Norwegian Ministry of Justice and the Police). The directorate has a full overview over developing vulnerable situations and looming perils that threaten society – in peacetime and in war. And, in the event of inadequate safety and preparedness measures, it takes the initiative for follow-up with the responsible authorities. The directorate has a special responsibility to ensure that society has a common comprehension of vulnerability, and it coordinates measures to reduce vulnerability (in cooperation with, for example, the 18 County Governors in Norway). A transition from traditional preparedness thinking to a more proactive safeguarding of life, health and the environment calls for cross-disciplinary cooperation. The question is to what extent barriers between professions (represented in different institutions) constrain this development. The National Office of Building Technology and Administration (under the Ministry of Local Government and Regional Development) is responsible for administering and interpreting Norwegian building regulations, and it has the authority to administer a centralized system of Approval of designers, constructors or controllers in the construction industry. The Directorate for Civil Protection and Emergency Planning and the National Office of Building Technology and Administration have a common responsibility to initiate collective efforts by institutions to reduce climate vulnerability in the built environment.

Strategies for climate change adaptation must, of course, be developed with due consideration for other agendas for change that to some extent may contribute to an improvement of these strategies, e.g. the general movement towards industrialization, prefabrication and off-site construction (Lowe, 2001). The development of increasingly Europeanized construction and construction products industries, and the continued development of Norwegian and international standards (especially the preparation of additional national appendices associated with the various types of climatic impact) are also important factors to be considered. The need for adjustments or alterations of the present and future building stock and building practice should be kept under close observation, based on the continuous monitoring of the development of regional- and local-level scenarios for climate change. A simple precautionary adaptation measure could be to choose solutions with a higher climatic safety level than considered necessary under the climate regime of today, where this may be considered cost beneficial. However, weighing cost and benefit in this context is certainly not straightforward and introduces new challenges to be considered.

Further studies on adaptation strategies need to explore the extent to which the industry considers geographically dependent climate change in the production of buildings. Furthermore, to what extent is local knowledge, technical and scientific information exchanged between the different actors, and what is encouraging or constraining locally adapted solutions? These questions are now being addressed through an ongoing investigation within the NBI Research & Development Programme ‘Climate 2000’ (Øyen *et al.*, 2005).

Conclusions

There are large uncertainties associated with the future performance of the built environment due to changes in external climatic impact. In order to develop adaptation strategies, effective ways must be found to strengthen institutional capacity. Cross-disciplinary risk-based management strategies, together with design guidelines that account for both historical local climatic conditions and potential future changes, can be an important step towards a more active and dynamic way of ensuring a high-quality construction process and a sustainable built environment in the light of the unknown risks of future climate change.

For large, complex building projects, there is an established tradition of using risk analysis methods. This tradition has not moved from large-scale to more ‘trivial’ building. Obviously, there are benefits to be gained from the introduction of modern risk-based management strategies within a greater extent of the construction industry. This paper discusses three different strategies: risk-based, precautionary and discursive. The choice of strategy is strongly dependent on the characteristics of the risk at hand. Facing the future risks of climate change, it is suggested that a flexible approach using a combination of these strategies can help reduce potential impacts. Reducing the potential for defects or damage through the development of technical and organizational preventive measures (a risk-based management strategy), while at the same time applying the precautionary principle (from the risk class 'Pythia') and discursive strategies in the design, construction and geographical localization of buildings, is likely to increase the robustness of the built environment in light of the unknown risks of climate change. A complementary approach to the risk-based, precautionary and discursive risk-management strategies could be to employ Bayesian methods, especially where sufficient regional information has been obtained.

For the described approach to risk management of future climate change impacts to be successful, it is necessary to ensure careful cooperation along vertical decision-making lines, i.e. from government regulatory bodies via local regulatory bodies and inhabitants, research communities and company management to the craftsmen on site.

A successful implementation of adaptation policies at the national level is dependent on a few key institutions' ability to initiate both government regulatory measures and local-level collective efforts to reduce climate vulnerability. In Norway, this would be the Directorate for Civil Protection and Emergency Planning and the National Office of Building Technology and Administration. NBI, as an independent institution developing technical guidelines that reaches out to almost all actors in the construction industry, and academic institutions such as the NTNU also have an important role to play in the development of strategies aimed at building awareness of the future risks of climate change and in the development of precautionary and cost–beneficial adaptation measures.

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Endnotes

[1] See http://www.met.no

[2] See http://www.wikipedia.org

Part B

Review of the Norwegian building stock and building practice

V. **Lisø**, K.R., Kvande, T. and Thue, J.V. (2006) Learning from experience – an analysis of process induced building defects in Norway. *Research in Building Physics and Building Engineering – Proceedings of the 3rd International Building Physics Conference* (Fazio, Ge, Rao & Desmarais eds), Taylor & Francis Group, London: 425-432

VI. **Lisø**, K.R., Kvande, T. and Thue, J.V. (2005) High-performance weather-protective flashings. *Building Research & Information*, **33**(1), 41-54.

VII. Kvande, T. and **Lisø**, K.R. (2006) Climate adapted design of masonry structures. *Building and Environment* (submitted).

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VIII. Meløysund, V., **Lisø**, K.R., Siem, J. and Apeland, K. (2006) Increased snow loads and wind actions on existing buildings: Reliability of the Norwegian building stock. *Journal of structural engineering* (in press).

Paper VIII is based on research presented in Siem, J., Meløysund, V., Lisø, K. R., Strandholmen, B., Prestrud, O., 2003: Snø- og vindlaster på eksisterende bygninger – Rapport fra prosjekt 1 og 2 i FoU-programmet "Klima 2000", Report 114, Norwegian Building Research Institute, Oslo [in Norwegian]. Vivian Meløysund, Kim Robert Lisø and Jan Siem had main responsibility for the planning and carrying out of the investigation, and have been the main authors of the paper. Kristoffer Apeland has contributed with his extensive experience within the field of snow engineering, especially related to regulations, rules and standards. Apeland have also contributed by improving outlines made by the main authors. Lisø initiated the investigation and wrote a first draft paper for the 5th International Conference on Snow Engineering in Davos, 2004.

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Learning from experience – an analysis of process induced building defects in Norway

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ABSTRACT: This paper presents a comprehensive review of process induced building defects investigated by SINTEF Building and Infrastructure in the 10-year period 1993–2002 (2,423 cases registered and described in 2,003 assignment reports). Defects related to the building envelope constitute 66% of the investigated cases. A bulk of the defects (76%) is related to moisture, and many types of building defects are recurring items, indicating a general lack of knowledge concerning fundamental principles of building physics. A wide range of classical problems is recorded, e.g. unfortunate design and use of materials, inaccurate craftsmanship, structure and composition of rendering layers and paint on porous, mineral building materials, inappropriate rendering layers on facade systems with rendering directly on thermal insulation, and insufficient efforts to protect against moisture in general. These findings support earlier investigations concluding that the construction industry is not able to learn from past experience and that the exchange of knowledge is not satisfactory.

1 INTRODUCTION

1.1 *Principal objectives and scope*

SINTEF Building and Infrastructure's archive of building defect assignments represents one of Norway's most important sources of knowledge on types of process induced building defects and related causes. This knowledge is now being thoroughly analysed. Preliminary registration work has been reported through work carried out by master students at NTNU (Sagen 2004, Bjerkevoll 2004, Bjerkevoll 2005) and some overall results were presented by Lisø et al. (2005a).

Ingvaldsen (2001) defines "process induced building defects" as absence or reduction of presupposed capacity that is discovered after a construction project has been completed and taken over by the owner, and which he demands to be repaired. Thus, process induced building defects bring about exceptional maintenance costs, i.e. cost that should not have incurred – or additional costs related to a more frequent maintenance than forecasted. All because the actors involved have not succeeded in fulfilling requirements in standardised or generally recognised methods or specifications. Defects caused by normal wear and tear are not defined as building defects.

The principal objective of the presented investigation has been to establish an electronic process induced building defects archive, adopting the definition above and based on building defect assignments carried out by the institute in the period 1964 until today. The work form a central part of a PhD study within the SINTEF Building and Infrastructure's research & development programme "Climate 2000" (Lisø et al. 2005b). The main objective of establishing such an archive is to allow for the preparation of a review of the Norwegian building stock and building practice in order to evaluate how different types of buildings and structures could be vulnerable to possible impacts of climate change due to global warming. The results will also be used in the further development of best-practice solutions and high-performance building envelopes in different climate zones.

There are obviously also other areas of application for this considerable source of experience-based knowledge. The results will finally be used as a basis for the development of more accurate criteria and Codes of Practice regarding the design and functionality of critical elements of buildings, and incorporated in the appropriate SINTEF Building Research Design Sheets.

This paper present results from an investigation of all process induced building defect assignments carried out by the institute in the 10-year period 1993–2002 (2,003 reports describing 2,423 incidents or cases of defects), together with a thorough description of the methodology applied. These assignments represent valuable examples for future learning.

1.2 *The extent of building defects in Norway*

The historical development of Norwegian building traditions implies both an adaptation towards different preconditions for use of buildings and varying styles of architecture, but also an adjustment towards the extreme climatic variations in Norway. Changes in building practice also reflect the economic development and new demands in standard of living. The extremely varied climate and topography in Norway puts great demands on the design and localization of buildings and the correct choice of materials and constructions. A definitive minimum requirement for a building is that it should tolerate to be left outside.

Natural disasters caused by extreme weather events are one of the major challenges confronting the built environment. However, the amount of building defects not covered by natural disaster insurance is also tremendous. The increasing demands in the construction industry for profit and shorter construction periods, combined with extremely varied climatic impacts during the construction process, prove to be a difficult circle to square (Lisø et al. 2003). Investigations carried out by SINTEF Building and Infrastructure indicates that the cost of repairing process induced building defects in Norway amounts to 5% of the annual capital invested in new buildings (Ingvaldsen 1994). Ingvaldsen also found that this estimate was in good agreement with 13 corresponding investigations or sources of information in other European countries (with a mean estimate varying between 3 and 5%). Correcting faults and repairing defects in buildings during the construction process is estimated to cost roughly the same amount as repairing buildings in use, e.g. another 5% (Ingvaldsen 1994). With an annual investment in refurbishment and new construction of NOK 130 billion (as in 2003), it is reasonable to estimate that approximately NOK 13 billion is being spent on repairing defects or damage to buildings every year.

The Danish Building Defects Fund is the primary source of information on building quality for the past 10–15 years in Denmark. The Fund carries out year-one and year-five inspections on all publicly subsidised housing. The Fund's database comprises information on more than 2.000 building defect inspections carried out by use of random sampling. Major deficiencies (the definition of "deficiency" is by and large equivalent to Ingvaldsen's definition) have been registered in 5% of the year-one inspections and in 25% of the year-five inspections (Byggskadefonden 2005).

1.3 *Government regulatory measures and building quality*

Ways to strengthen institutional capacity to implement appropriate building performance requirements and standards, and thus reducing the sensitivity of the built environment, is an important element in adaptation to climate change (Lisø et al. 2003), and naturally also when trying to adapt the built environment to the prevailing climate. The present general trend in legislation and regulation away from prescriptive rules to performance-based codes will increase the need for interaction between regulatory decision makers and substance matter experts (Rasmussen 1997).

The most important government regulatory measure to ensure adherence to building codes and standards is the Technical Regulations under the Norwegian Planning and Building Act (PBA), which since 1997 have been performance-based. The principal motive for a transition from a prescriptive code to a performance-based code in Norway was to contribute to an increase in the quality of buildings and a reduction of the amount of building defects. Preliminary findings from a case study of process induced building defects suggest that the adoption of a performance-based building code has indeed led to a positive change in quality (Mehus et al. 2004). However, even if the amended PBA appears to be contributing towards improved quality of construction, defects, flaws, and premature damage are still flourishing in new construction. Furthermore, design of details crucial to durability and service life of buildings is often omitted or they are improvised on site (Stenstad et al. 2005).

The transition from a prescriptive to a performance-based code has strengthened the demand for supporting standards and design guidelines. The Building Research Design Sheets in the SINTEF Building Research Series comply with the performance-based requirements in the building code, and are important references to "pre-accepted" solutions in the technical regulations. The principal objective of the Design Sheets is to adapt experience and results from practice and research in such a way that they can be of practical benefit to the construction industry. The main purpose is to provide guidelines, solutions and recommendations that encourage high quality in the planning, design and construction of buildings. The series consists of more than 800 design sheets, the first sheets being published in 1958. It is by far the most used planning and design tool amongst Norwegian architects and engineers and is found on nearly all construction sites. The Design Sheets are continuously being updated to comply with the building code and experience-based knowledge.

However, the technical solutions presented in the Building Research Series are in general meant to have a reliability level suitable for all parts of the country. The "robustness" of the Norwegian building stock, including the development of methods for classifying different climatic parameters and their impact on building envelope performance, are now being addressed as part of the research & development programme "Climate 2000".

An important aspect of the programme will be the preparation of a thorough overview of the relevant regional climatic loads that should be taken into account during the total life cycle of the built environment, in order to develop climate adapted high-performance technical solutions, with a reliability level that reflects the different climatic impacts the constructions or materials actually are being exposed to. The basis for calculating characteristic wind and snow loads on buildings in different parts of the country is regulated by Norwegian and international standards. At present there are very few, if any, corresponding, easily accessible design guidelines for assessing geographically dependent climatic exposures related to external moisture loads.

2 METHODOLOGY

SINTEF Building and Infrastructure's project archive contains information on more than 33,000 projects in a wide range of disciplines carried out by the institute in the period from 1964 until today. Key data on these projects are stored in a Microsoft SQL-server database.

The institute has undertaken analyses of building defects for more than 50 years, both on behalf of the construction industry and in comprehensive field investigations. Information on these assignments is filed in the institute's central archive, and registered electronically in the SQL-server database. Information on the following key data is registered electronically: Client, project number, project leader, report date, age of the building, building address, construction method, keywords and summary. The summary provides overall information on the type, location, scope and cause of the defect.

However, owing to incomplete summaries and keywords in the database, and also insufficient registration routines for building defect assignments in the early years of registration, a tremendous and time-consuming effort has been undertaken to extract process induced building defect assignments from the archives. Several thousand projects register as hits when searching with "defect" as the keyword. Unfortunately, not all building defect assignments are found in the database even when searching for "defect". Therefore, a comprehensive investigation of paper copies of assignment reports has been undertaken to isolate the process induced building defect assignments. Detailed information on each assignment is obtained from the paper copies, which are being thoroughly analysed as part of the ongoing investigation and establishment of the institute's process induced building defects database.

The information on each assignment is stored in a spreadsheet program, linked electronically to information in the SQL-server database, allowing for in-depth statistical analyses. Altogether it is found that the institute has approximately 5,000 process induced building defect assignment reports from the period from 1964 until today.

3 RESULTS

The inflow of building defect assignment reports to the project archive is based on commercial consultancy assignments from different actors in the construction industry, and thus do not represent a systematic or in any way planned selection of building defect cases.

Figure 1 presents a distribution of registered building defects distributed by type of clients.

Figure 2 presents a distribution of building defects by building type. 61% of the cases of defects or damage are related to residential buildings. 38% of the

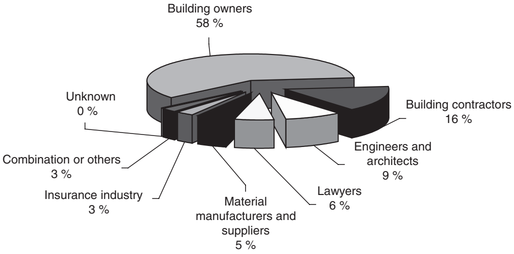

Figure 1. Process induced building defect cases for the 10-year period 1993–2002 (a total of 2,423 building defect cases), distributed by type of client.

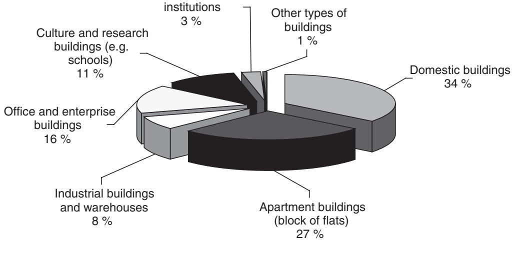

Figure 2. Process induced building defect cases for the 10-year period 1993–2002 (a total of 2,423 building defect cases), distributed by building type.

Table 1. Existing stock of residential buildings distributed by building type and county, as of January 2005 (source: Statistics Norway, www.ssb.no*).

	Total	A	B	C	D	E
Total	1,400,727	1,104,641	134,496	128,956	28,547	4,087
Østfold	82,498	65,255	8,585	7,389	1,075	194
Akershus	140,349	97,200	17,287	23,707	1,794	361
Oslo	65,810	23,922	12,962	18,792	10,032	102
Hedmark	75,868	67,956	3,985	3,296	431	200
Oppland	73,260	65,182	4,929	2,477	391	281
Buskerud	78,526	65,247	7,562	4,681	855	181
Vestfold	69,649	56,413	6,353	5,814	872	197
Telemark	58,874	52,593	3,141	2,340	606	194
Aust-Agder	38,133	35,177	1,460	1,239	141	116
Vest-Agder	50,920	40,513	4,270	5,357	616	164
Rogaland	121,408	98,408	13,079	8,461	1,213	247
Hordaland	129,218	94,894	11,183	17,550	5,333	258
Sogn og Fjordane	40,206	35,701	2,314	1,907	131	153
Møre og Romsdal	82,274	67,995	8,005	5,342	733	199
Sør-Trøndelag	78,334	56,667	11,291	7,374	2,533	469
Nord-Trøndelag	47,596	40,558	4,060	2,477	292	209
Nordland	88,310	74,174	7,509	5,641	692	294
Troms	51,597	45,141	3,336	2,407	586	127
Finnmark	27,897	21,645	3,185	2,705	221	141

A = Detached house; B = House with two dwellings; C = Undetached house, house built together and house with 3 or 4 dwellings/ D = Block of flats (multi-dwelling building); E = Residences for communities

* An overview of the existing stock of non-residential buildings (2,285,665 buildings) can also be found at this website.

total numbers of buildings in Norway are residential buildings. i.e. buildings for residential purposes are over-represented in the archive. An overview of the Norwegian stock of residential buildings is given in Table 1.

Domestic buildings are e.g. detached houses, semi-detached houses, undetached houses, houses built together and holiday homes. Apartment buildings are multi-storey block of flats. Industrial buildings and warehouses, and hospitals and health institutions, are self-explanatory. Office and enterprise buildings include e.g. hotels and congress buildings, shopping centres and military buildings. Culture and research buildings are defined as schools and other educational establishments, laboratories, museums, libraries, churches, indoor swimming pools, sports buildings, kindergartens, community centres and castles. Other types of buildings are e.g. prisons.

Figure 3 presents an overview of building defects distributed by localisation of defects. Defects related to the building envelope constitute 66% of the investigated cases. Technical installations are here defined as e.g. electric, heating, cooling, ventilation and sanitation installations. Defects incurred to technical installations do not in any way reflect the actual level of defects to such installations in Norway. It rather expresses that this is an area of expertise in which the institute traditionally have had few assignments. The term “other building components and assemblies” are used to categorise elements not to be studied in this investigation, namely all elements not forming part of a buildings envelope (e.g. inner walls, stairs and other internal components). These cases should of course be subject to further inquiries, but then as part of research aiming at solving challenges in the pursuit of enhanced indoor quality in the built environment.

In Figure 4 an overview of sources of defects is given. This investigation focuses on defects related to moisture, which reply for as much as 76% of all cases. In recent years, more attention has been paid to the negative implications moist materials have on indoor air quality and health. The link between dampness and health has been scientifically demonstrated by numerous epidemiological surveys. Such surveys have been summarised in a Nordic research project (Bornehag et al. 2001).

The categorisation of defect sources is chosen to allow for a simple classification of the main impact

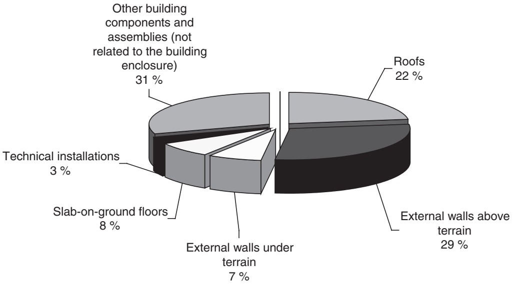

Figure 3. Process induced building defect cases for the 10-year period 1993–2002 (a total of 2,423 building defect cases), distributed by localization of defects.

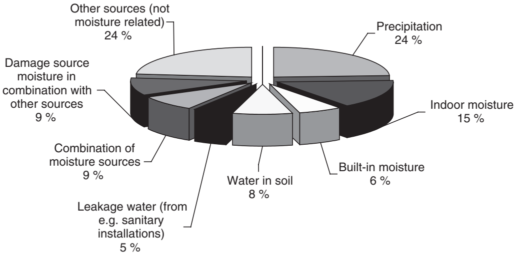

Figure 4. Process induced building defect cases for the 10-year period 1993–2002 (a total of 2,423 building defect cases), distributed by source of defects.

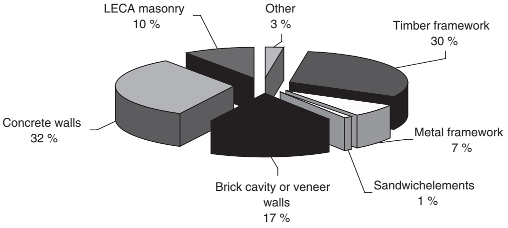

Figure 5. Defect cases for the 10-year period 1993–2002 concerning external walls above terrain, distributed by type of wall (587 cases, 29% of the total amount of building defects).

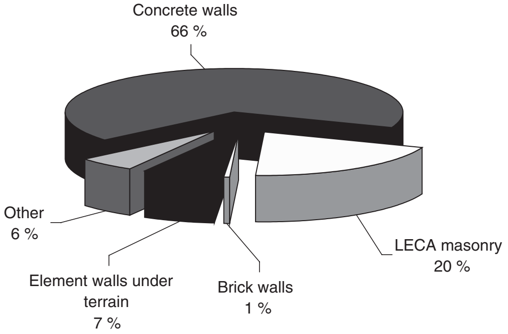

Figure 6. Defect cases for the 10-year period 1993–2002 concerning external walls under terrain, distributed by type of wall (145 cases, 7% of the total amount of building defects).

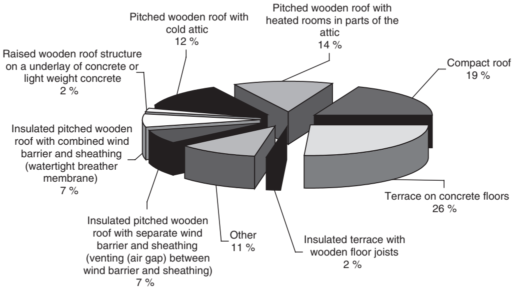

Figure 7. Defect cases for the 10-year period 1993–2002 concerning roofs, distributed by type of roof (465 cases, 22% of the total amount of building defects).

responsible for the defect. This again enables fast registration, while at the same time providing an overall illustration of the cause of defects. A more thorough analysis of defect causes calls for in-depth studies of each assignment report. Precipitation, often in combination with wind, is a self-explanatory climatic impact. Indoor activity, humans, animals and plants produce indoor moisture. Built-in moisture is moisture in both materials and constructions. Defects related to water in soil are due to insufficient draining and circumstances related to the outside terrain. 9% of the cases are related to moisture in combination with other sources. These other sources are often reinforcement corrosion and sulphate attack. 24% of the investigated cases are not moisture related at all.

In Figures 5–7 building defects concerning external walls above terrain (i.e. ground level), external walls under terrain and roofs respectively are broken down into distributions by type of structure. Only 30% of the building defect cases related to external walls above terrain is related to timber frame walls. The bulk of defects related to walls above terrain are found on walls made out of porous mineral building materials – with defects on rendered facades by far being the most common exterior surface problem.

Approximately 20% of the building defects are reported within the first year, and about 48% of the defects are reported within 5 years after completion of the building (Fig. 8).

A bulk of the defects is related to moisture, and many types of building defect cases are recurring items, which indicate a general lack of knowledge concerning fundamental principles of building physics. A wide range of classical problems has been recorded, as for example unfortunate design and use of materials, inaccurate craftsmanship, structure and composition of rendering layers and paint on porous, mineral building materials, inappropriate rendering layers on facade

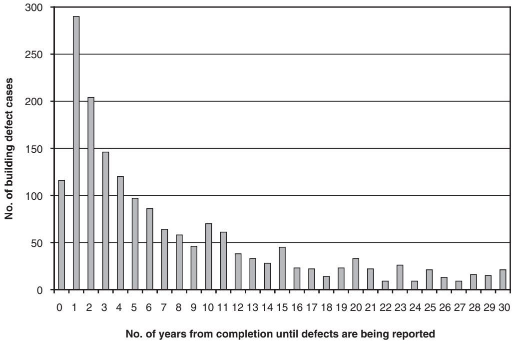

Figure 8. Process induced building defect cases for the 10-year period 1993–2002, distributed by number of years from completion until defects are being reported.

systems with rendering directly on thermal insulation, insufficient efforts to protect against precipitation and insufficient efforts to protect against moisture in general. These findings are supporting earlier investigations concluding that the construction industry is not able to learn from past experience and that the exchange of knowledge in construction projects is not satisfactory (e.g. Lisø et al. 2000).

The building defects archive reveals serious deficiencies in the construction industry with regard to knowledge about correct design and construction of buildings in Norway. These findings are also supported by earlier case studies of building defect assignments carried out by the institute. Lisø et al. (2005c) present a review of typical problem areas associated with weather-protective flashing. A total of 175 assignment reports associated with defective or damaged flashing from the period 1963–2001 were analysed. The investigation clearly showed that certain faults and deficiencies are recurring items. Windowsill/weatherboard flashings comprised as much as 41% of the building defect cases associated with weather-protective flashing. Defects in connection with parapet flashing comprised 27% of all cases included in this investigation. With few exceptions, instances of flashing defects are located in Norway's coastal areas.

A review of the archives regarding process induced masonry defects showed that inappropriate flashing techniques were involved in approximately 25% of all the masonry defect cases (Kvande & Lisø, submitted). Furthermore, the last mentioned investigation concludes that shrinkage and thermal expansion/contraction without the necessary countermeasures are the most common cause of masonry defect, registered in one third of all cases of defects analysed (302 process induced building defect assignments related to masonry in the 20-year period 1983–2002). This investigation also reveals that two thirds of all cases comprise faults in the execution of the actual rain barrier (non water-tight mortar joints and rendering), drainage from the air gap (insufficient air gaps, mortar bridges between outer leave and rear wall as well as missing drainage openings at bottom of wall) and the execution of window and parapet flashing.

4 DISCUSSION AND LIMITATIONS

The analysis is based on building defect assignments carried out by SINTEF Building and Infrastructure and thus cannot aspire to represent a complete and definitive overview of process induced building defects in Norway. In geographic terms, building defect assignments forming part of the investigated 10-year period have been carried out in 182 municipalities out of a total of 436 municipalities in Norway. However, a major part of the cases of defects are located in municipalities near SINTEF Building and Infrastructure's offices in Oslo and Trondheim. This is due to the institute having easier access to building defect assignments in its vicinity. The municipalities of Oslo and Trondheim alone reply for 38% and 11% of the investigated cases respectively.

There is naturally a wide range of causes as to why the different actors within the industry contacts SINTEF for an expert opinion, assessment or investigation of a building defect incident. In most cases the client is concerned with the extent of the defects, and loss of reliability or reductions in lifetime of the component exposed to damage. The clients also often want advice as to how the defect or damage should be repaired.

In some cases the institute is addressed to settle a dispute between different actors involved in the construction process. The institute is also used as independent experts in cases to be solved by the judicial system. It is therefore important to emphasise that only a small part of the total amount of process induced building defects in Norway emerges in the SINTEF Building and Infrastructure's building defects archive.

The following conditions or circumstances will contribute to a restriction in the selection of building defect assignments:

- The probability that a certain defect will emerge in the archive will be higher the more difficult it is to find a good solution to the problem, or the more ambiguously conditions regarding responsibility are described.
- It is reasonable to assume that the costs involved in the assignment of the institute as expert advisors make professional actors dominant. This probably also explains the large amount of complex and expensive defect cases in the archive. Changes in the institute's time rates compared to the general economic trend in the society, and changes in the institute's price policy, could also entail changes in

the amount and type of defects to be registered in the archive.
- It is reasonable to assume that the inflow of assignment reports is strongly related to areas of expertise where SINTEF Building and Infrastructure has a good reputation. Thus, changes in the institute's competence profile could entail changes in the amount and type of building defect assignments.

One of the major advantages with the archive is clearly the large amount of assignments over a long time period. Also, the archive contains thorough descriptions of cause, extent and preventive actions on complex building defect cases, investigated and described by highly competent researchers. Despite the presented investigation having quantitative shortcomings in terms of general validity, it is an important step towards a qualitative identification of problem areas.

The ongoing establishment of the described building defects archive will be an important tool in both the continuous efforts towards higher quality in the construction industry and the development of strategies aiming at learning from experience. It will also be a significant instrument in the development of appropriate preventive actions. The archive will finally be an important element in the continuous development of more accurate criteria and Codes of Practice regarding the design and functionality of critical elements of buildings in the SINTEF Building Research Design Series.

5 FURTHER WORK

Empirical observations and modelling increasingly point to global warming and long-term changes in the climate system. The Intergovernmental Panel on Climate Change concludes that most of the warming observed over the last 50 years is attributable to human activities, and that anthropogenic climate change is likely to persist for many centuries. The presented review of building defects will be further developed and used to prepare a review of the robustness of the Norwegian building stock and building practice. SINTEF Building and Infrastructure, as an independent institution developing technical guidelines that reaches out to almost all actors in the construction industry, and academic institutions like NTNU have an important role to play in the development of strategies aiming at building awareness of the future risks of climate change and in the development of precautionary and cost beneficial adaptation measures (Lisø 2005).

At present, building design codes, standards and operational procedures are based on historic weather data. The existing building stock is in the next decades likely to be exposed to significantly different climatic strains than they are today, due to climate change. The robustness of the Norwegian building stock will be assessed through analysis of statistical data, along with SINTEF Building and Infrastructure's experience with building defects. Statistical data for e.g. building types, year of construction and geographical localisation of the approximately 3.68 million registered buildings in Norway are available in the Ground Property, Address and Building Register (GAB). Approximately 1.4 million buildings are for residential purposes. The municipalities record data in GAB (all buildings in Norway larger than 15 m^2 are to be recorded in the register with a code for building type and coordinates). Historic trends in the design and construction of buildings and built environments will also be studied. Historic weather data and statistical data from insurance companies (natural damage) will serve as an enlarged basis for the analysis.

The design of building envelopes should be expected to be the result of choices based on optimally utilised information and knowledge on both building technology and the different impacts the buildings are exposed to (Nordvik & Lisø 2004). Several sources of uncertainties exist related to both scenarios for global climate change, and to the effects of global warming on regional- and local-level climate in different parts of the country. However, an increased focus on the impacts of different climatic parameters on building envelope performance will lead to a more climate adapted design in new construction, and also a more robust performance of existing buildings.

The work presented here allows for in-depth analyses of causal relations of different types of building defects on a wide variety of building envelope elements. Final results from these ongoing investigations, together with comparisons with prospective corresponding international research within this area, will be published in due course.

6 CONCLUDING REMARKS

Defects related to the building envelope constitute 66% of the investigated process induced building defect cases in the 10-year period 1993–2002. Moisture as the main source causing the defect replies for as much as 76% of all investigated cases in the 10-year period. Many types of building defect cases are recurring items, which indicate a general lack of knowledge amongst the different actors in the construction industry concerning fundamental principles of building physics in particular.

It is possible to reduce the amount of building defects in Norway. This would require a determined and active effort in several areas and by several actors within the construction industry. To reach future national defined goals on building defect reduction it is crucial to be familiar with both the technical and process induced causes initiating defects or damage. A future national building defects archive, in which the here-described archive should be a central contribution, would be an important part of this work; as such an archive would shed light on the underlying causes of defects and enable assessment of preventive actions.

The presented process induced building defects archive will also be an important educational tool in the establishment of knowledge and experience on building defects amongst academic institutions and different actors in the construction industry.

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High-performance weather-protective flashings

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Typical problem areas associated with weather-protective flashing are identified, based on a comprehensive investigation of building damage cases in Norway. A total of 175 assignment reports associated with damaged flashing for the period between 1963 and 2001 are analysed. The investigation clearly shows that certain faults and deficiencies are recurring items. Windowsill/weatherboard flashings comprise as much as 41% of the building damage cases associated with weather-protective flashing. Damage in connection with parapet flashing comprises 27% of all cases included in this investigation. With few exceptions, instances of damage are located in Norway's coastal areas. Existing flashing solutions in the Norwegian Building Research Institute's Building Research Design Sheets have been further developed, based on the results from the analysis. Improved high-performance flashing solutions are presented for a number of typical problem areas. An illustrated summary of problems frequently encountered with different flashing variants is also presented. Finally, recommended best-practice flashing solutions for a number of typical problem areas are provided. The results will be implemented in the Building Research Design Sheets, and will also be used as a basis for the carrying out of new field studies and laboratory investigations.

Keywords: building damage, building defects, building enclosure, building pathology, building performance, building stock, climate adaptation, climatic impact, durability, weather-protective flashings, Norway

S'appuyant sur une enquête approfondie relative aux dommages causés à des bâtiments en Norvège, l'auteur recense les problèmes types que l'on rencontre avec les solins d'étanchéité. Il analyse 175 rapports de mission portant sur des solins endommagés au cours de la période 1963–2001. Il ressort clairement de cette enquête que certains défauts et déficiences sont des événements récurrents. Quarante et un pour cent des dommages analysés concernent des solins d'étanchéité d'appuis de fenêtres et de parements. Les dommages causés à des solins de parapets comptent pour 27% de tous les cas analysés. A quelques exceptions près, les dommages ont été observés dans des zones côtières de Norvège. Les solutions proposées par l'Institut norvégien de recherche sur le bâtiment ont été affinées sur la base des résultats de cette analyse. L'auteur décrit des solutions faisant appel à des solins à hautes performances et applicables dans un certain nombre de cas. Il présente également un résumé illustré de problèmes que l'on rencontre fréquemment avec divers types de solins. Pour terminer, il recommande des solutions basées sur les meilleures pratiques en matière de solins. Les résultats figureront sur les fiches techniques de l'Institut de recherche norvégien sur le bâtiment et serviront également de base à de nouvelles à mener sur le terrain et à des enquêtes en laboratoire.

Mots clés: dommages aux bâtiments, défauts des ouvrages de construction, enveloppe des bâtiments, pathologie des bâtiments, performance des bâtiments, parc immobilier, adaptation au climat, impact du climat, durabilité, solins d'étanchéité, Norvège

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Introduction

Background

The principal function of weather-protective flashings is to serve as an outer rain shield in a two-stage tightening, and to act as a mechanical safeguard for any underlying tightening layer, e.g. roofing. Flashing should be designed and installed so that precipitation is directed away from the structure and not be allowed to penetrate beneath the flashing with the risk of leaks. The flashing material must withstand the climatic loads to which it is exposed. Achieving such results often proves difficult in practice. In addition, the appearance of the flashing must satisfy the aesthetic requirements demanded of the structure of which it forms a part. Quite often, there is a conflict between technical or functional requirements and aesthetic demands.

The cause of most deficiencies connected with flashing can usually be traced back to workmanship by operatives other than skilled tinsmiths. Installation of flashings by unskilled operatives often results in poorly planned and executed work. The flashing can be incorrectly designed, incorrectly installed and/or incorrectly fastened to the base. A lack of understanding about the correct design and construction of weather-protective flashing can lead to water leakage and other damage occurring soon after completion. In addition, many architects tend to make flashings as marginal as possible (e.g. reducing the turndown along the facade). This often results in discoloration and staining of otherwise fine facades.

Internationally, several scientific studies have focused on building damage associated with weather-protective flashings. McDonald *et al.* (1997) reported the results of wind-tunnel and full-scale measurements of wind pressure on metal edge flashings. Baker (1965) focused on faulty flashings at interruptions and terminations of roofing membranes as a frequent source of leakage in a paper on flashings for membrane roofing, and stated that a clear understanding of the function of flashings, the forces they are subjected to and the limitations of the materials commonly used is necessary for successful design. The development of flashing solutions and techniques in Norway are primarily based on experience and field investigations of unfortunate or ill-advised solutions (e.g. NBI, 1991). Thus, there is a clear need to obtain further knowledge on the performance and durability of the most commonly used solutions.

Climatic impact and building damage in Norway

Climatic impact from precipitation, wind, temperature and exposure to the sun causes extensive degradation and damage to the built environment every year. The understanding of how degradation and damage can best be reduced is of significant importance in the design and construction of buildings (Lisø *et al.*, 2003b). Natural disasters caused by extreme weather events are, of course, one of the major challenges confronting the built environment. However, the amount of building damage not covered by natural disaster insurance is tremendous. The increasing demands in the construction industry for economy, progress and quality, combined with the existence of large amounts of precipitation during the construction process, prove to be a difficult circle to square (Lisø *et al.*, 2003c). Investigations carried out by the Norwegian Building Research Institute (NBI) have shown that the cost of repairing process-related building damage in Norway amounts to 5% of the annual capital invested in new buildings (Ingvaldsen, 1994). Correcting faults and repairing damage in buildings during the construction process is estimated to cost roughly the same amount as repairing buildings in use, e.g. another 5% (Ingvaldsen, 2001).

As a rule, building damage starts to develop shortly after completion of the building. Poor planning, design and implementation of flashing, with consequential moisture damage to underlying or adjacent structures, are the direct or contributory cause of much of this damage. Complicated geometry makes great demands on flashing techniques. Very often, the flashings are not seen as an integral part of the building enclosure.

Climate change will entail new conditions for several sectors of Norwegian society, including the construction industry. The climate system is likely to undergo changes, regardless of the implementation of abatement policies under the Kyoto Protocol or other regimes. A special issue of *Building Research & Information* (**31**[3–4]) (2003) posed the questions of 'what policies, strategies, practical measurements and underpinning research will be needed to adapt the built environment to climate change?' While the full range of impacts resulting from these changes is still uncertain, it is becoming clear that adaptation to climate change is necessary and inevitable (Lisø *et al.*, 2003c).

Norway's climate is extremely varied, the rugged topography being one of the main reasons for large local differences over short distances. Climate scenarios for Norway emanating from the project 'Regional Climate Development under Global Warming' (RegClim; http://www.regclim.met.no) suggest changes in mean and extreme temperature, precipitation and wind. Precipitation scenarios for Norway conform to those at the global scale in that they assume increased precipitation in existing wet areas and periods. Climate change will have different climatic impacts on different types of buildings depending on scale, use, design, construction and location. The amount of building damage in Norway clearly illustrates that it is not only the extreme weather events that should be studied to ensure long-term adjustments to a climate regime with greater variations (Lisø *et al.*, 2003a). Driving rain (rain combined with wind) is the most critical climatic load that should be taken into account during the planning, design, construction, management, operation and maintenance of weather-protective flashings (Geving and Thue, 2002; Kvande and Lisø, 2002). Marginal flashing solutions are particularly vulnerable.

Principal objectives and scope

The Technical Regulations or building codes under the Norwegian Planning and Building Act since 1997 have been performance-based. The transition from a prescriptive to a performance-based code has strengthened the demand for supporting standards and design guidelines. The NBI Building Research Design Sheets in the Building Research Series comply with the performance-based requirements in the building code, and are an important reference to pre-accepted solutions. The principal objective of the Building Research Design Sheets is to adapt experience and results from practice and research in such a way that they can be of practical benefit to the construction industry. The main purpose is to provide guidelines, solutions and recommendations that encourage high quality in the planning, design and construction of buildings. The series consists of over 850 design sheets, the first 'sheets' being published in 1958. They are continuously being updated to comply with the building code. It is by far the most used planning and design tool by Norwegian architects and engineers, and is being found on nearly all construction sites (with about 22 000 subscribers and over 100 000 users).

The principal objective of the presented investigation has been to discover and analyse typical problem areas regarding weather-protective flashing in severe climates and to develop further best-practice solutions. The results will be incorporated in the appropriate Building Research Design Sheets.

Analysis of building damage associated with weather-protective flashings

Method

This presentation of typical problem areas associated with weather-protective flashing is based on a thorough investigation of building damage cases in NBI's project archives. Commonly used flashing solutions have been revised and improved, based on the results from the analysis. Representatives from the Norwegian Association of Ventilation- and Tinsmith Companies have verified the revised high-performance flashing solutions presented for a number of typical problem areas.

NBI's project archives, together with the NBI Building Research Series, represents one of Norway's most important sources of knowledge on types of building damage and related causes. Key data for all the projects carried out by NBI since 1963 are now registered in a database making it possible to trace, for example, damage reports dealing with problems associated with flashing. The NBI's archives reveal serious deficiencies in the construction industry with regard to knowledge about the correct design and construction of weather-protective flashing. A review of the project archives regarding masonry damage showed that inappropriate flashing techniques were involved in approximately 25% of all the masonry damage cases analysed by the NBI (Kvande *et al.*, 2003). Inappropriate flashing techniques, in this context, include faulty door, window and parapet flashings, faults in down pipes and roof guttering, and faulty installation of doors and windows.

Since 1953, the NBI has undertaken analyses of building damage, both on behalf of the construction industry and in comprehensive field investigations. An ongoing investigation of building damage cases in NBI's project archives indicates that more than three-quarters of the total number of buildings examined between 1988 and 2002 had suffered water and/or moisture damage (results from the investigation will be published in due course).

Altogether, the NBI has more than 6000 building damage assignment reports in its project archives for 1963–2001 inclusive. The data are stored in a Microsoft SQL-server database. Information on the following key data is registered electronically in the archives: client, project number, project leader, report date, built (year), building address, method, keywords and summary. The summary provides overall information on the type, location, scope and cause of the damage. Paper copies of each damage assignment reports are easily accessible in the institute's central archives. Detailed information on each assignment is obtained from the paper copies. A total of 175 assignment reports associated with damaged flashing were analysed as part of this investigation. The registration work is mainly carried out by Harila (2002).

Results

Table 1 shows the types of flashing for which damage problems have been registered. The names of the flashing variants are the same as those given in the damage reports. Windowsill and weatherboard flashings stand out as the dominant problem area. As much as 41% of all cases of damage are associated with windowsill, weatherboard (lower and upper) and door flashing (lower and upper) flashing. Damage associated with parapet flashing accounts for about one-quarter of all cases of damage in this survey (27%).

Table 1 Ranking of flashing types according to the percentage of building damage cases associated with the different types of flashing (based on 175 investigated assignment reports)

	Type of flashing	Building damage cases (%)
A	Window, windowsill and weatherboard flashing (upper and lower). Door flashing (upper and lower)	41
B	Parapet flashing (including balcony flashing and balustrade flashing)	27
C	Chimney flashing	9
D	Wall flashing and horizontal flashing	6
E	Roof flashing and ridge flashing	4
F	Other types of flashing	13

Damage in connection with weather-protective flashing is most prevalent in coastal areas, which are subject to strong winds and penetration of driving rain and snowdrift.

Table 2 presents a ranking of typical weak points irrespective of the type of flashing.

Evaluation of results

This paper presents a ranking of damage in connection with the design and construction of flashing. However, the survey presented has some limitations. Analysis is based on NBI's project archives and thus cannot aspire to represent a complete and definitive overview of damage associated with weather-protective flashing in Norway. In geographical terms, a majority of the cases of damage are near NBI's offices in Oslo and Trondheim. This is due to the NBI having easier access to building damage assignments in its vicinity. Furthermore, the ranking has not been evaluated against the amount of different types of flashing. For example, there are usually many more metres of parapet, windowsill and weatherboard flashing on a building than, for example, for a chimney flashing.

Despite the investigation having quantitative weaknesses, it must nevertheless be regarded as being an important qualitative step towards identifying problem areas. The presented ranking of flashing types and typical problem areas were in good accordance with the Norwegian Association of Ventilation- and Tinsmith Companies own comprehension of typical problem areas (S. Tybring Haug and T. Opheim, personal communication/interview, Norwegian Association of Ventilation and Tinsmith Companies, Oslo, 2003). Evensen (2003) used interviews as a method for the mapping of typical flashing construction/workmanship failures. The results from the analysis presented herein are in good agreement with results obtained from Evensen's interviews with a number of tinsmiths and other actors in the construction industry dealing with the planning, design and construction of weather-protective flashings.

Table 2 Ranking of typical weak points irrespective of the type of flashing according to the number of building damage cases associated with the source of damage. A total of 175 case reports were investigated. Two or more weak points occurred in several reports

Typically weak points (source of damage)		Number of building damage cases
I	**Fastening**. Screws and/or nails puncture the flashing, thus providing an opportunity for water penetration. Insufficient construction/workmanship and/or anchoring are also a common problem	86
II	**Jointing**. Overlap joints are very common and frequently cause leaks. Always use welted flashing, possibly combined with a sealant, and without clipping off the corners of bends in the flashing	65
III	**Drainage from the flashing**. Flashing must be inclined if build up of water pressure against joints and/or connections is to be avoided	44
IV	**Turndowns along the facade**. Short turndowns make it possible for the wind to force water underneath the flashing	39
V	**Ends and corners of the flashing**. Lack of three-dimensional thinking when shaping the ends and corners of flashings can easily lead to leaks	39
VI	**Finishing-off**. Finishing off with insufficient drip edging prevents water being directed away from the facade, resulting, for example, in a moist or soiled facade	23
VII	**Ventilation gaps**. Air access to ventilated cavities, in both inward and outward directions, must not be blocked	16
VIII	**Tightening layer behind the flashing**. Weather-protective flashing usually forms the rain shield (drainage flashing) of a two-stage tightening. A poorly executed tightening behind the flashing can easily cause leaks. Besides which, the wind-barrier layer behind the flashing must withstand moisture loads	15
IX	**Holes**. All puncturing and perforation of flashings provide opportunities for leaks	10
X	**Flashing edges**. Flashing edges must have a wrap-over if corrosion is to be avoided	9

Typical problem areas and recommended solutions

Introduction

This section presents examples of typical problem areas and causes of damage regarding weather-protective flashing, based on the results from the investigation of building damage assignment reports in NBI's project archives (Tables 1 and 2). Examples of ideal high-performance model solutions for harsh climates are also provided, based on the performance requirements for flashings summarized below.

Weather-protective flashings should do the following:

- ensure that a negligible amount of precipitation penetrates as far as the wind barrier behind
- direct water away from the facade
- allow airflow for appropriate ventilation of cavities and air gaps
- resist the climatic and mechanical loads to which they are exposed
- be designed and fastened so that they do not damage, or become damaged by, the materials in the adjacent building structures

Experience from other Nordic countries is used (e.g. Plåtslageriernas Riksförbund, 2002). Typical problem areas and recommended solutions are presented in more detail by Kvande and Lisø (2002). In this overview of problem areas and causes of damage, the names of the flashing variants adhere mainly to the terms and definitions given in Norwegian Standard 3420-S4 (1999). For corresponding English equivalents, see the Appendix.

Jointing and fastening

The use of folded welts (or seams) is far preferable to, for example, welding or gluing when jointing extended lengths of flashing. Sealant should always be used when fastening flashings in connection with sheet-metal roofing. Folded welts can give leakage points at bends in the flashing when poorly executed (Figure 1). It is often found that attempts have been made to seal leaks in flashing joints and transitions by using extra screws or some sort of mastic. Using screws normally makes matters worse. The use of mastic as a sealant in connection with jointing is common practice, but such sealing has only a short life span due to thermal expansion/contraction of the sheet metal.

Folded welts facilitate the absorption of thermal expansion/contraction. In order for the folded welt to absorb temperature-induced movement, the spacing between joints should not be too large (recommended lengths are given in Norwegian Standard 3420, 1999). The use of overlap jointing is generally not advisable.

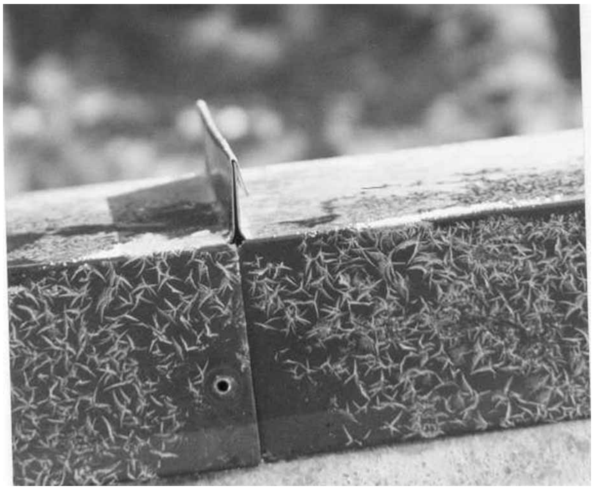

Figure 1 Poorly executed folded welt on parapet flashing. The under-flashing is missing. Source: Norwegian Building Research Institute, Oslo

The strength of the flashing's fastening must be sufficient to prevent it from being blown off by locally encountered wind forces. When securing flashing with screws or nails, it is essential that fastening points be positioned where the structure will not be exposed to water pressure. Welted flashing (joints) should be recommended as a principal rule. By anchoring the flashing via the folded welts, perforation is avoided. When using screws, one must always choose screws with rubber washers to ensure that the seal will last for as long as possible. Unless exposed nail heads are suitably covered, the use of nails offers a very vulnerable solution in relation to water penetration.

Flashing edge

Open-ended flashing edges, among other features, must have a wrap-over to prevent corrosion. Besides which, finishing off without a wrap-over leaves a sharp edge that can cause personal injury. To lead water from the flashing away from the facade, the finished edge of the flashing must be given a drip edge. Figure 2a shows examples of flashing edge designs where the drip edge has been omitted and where water is being directed to places where it is unwanted. Recommended solutions are shown in Figure 2b. Flashing edges lacking support or reinforcement are also prone to damage when exposed to wind loads or to possible mechanical loads.

Windowsill and weatherboard flashing

In contrast to most other types of flashing, windowsill flashings are generally installed with flashing as

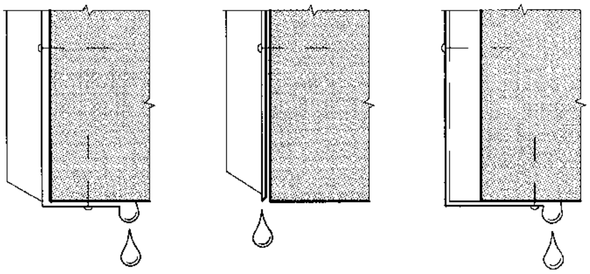

Figure 2a Unsatisfactory design of flashing edging. The drip edge is missing and rainwater is not led away

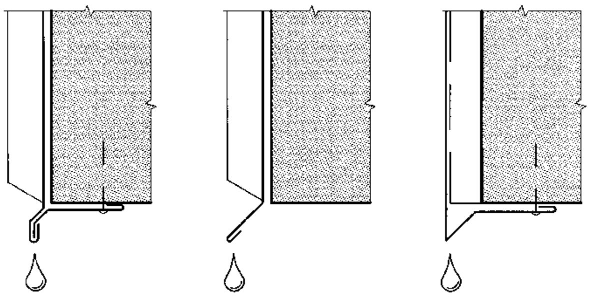

Figure 2b Examples of the recommended design of open-ended flashings. Water from the flashing drip edge is directed away from the facade. Wrapped-over edges help prevent edge corrosion

the sole tightening layer. This makes great demands on the design and installation of the flashing. The types of faults and deficiencies discovered vary to a certain extent.

The most common causes of damage associated with windowsill flashings are poor rendering of flashing edges against window recess (Figure 3a), and the flashing having neither an end turn-up nor a satisfactory fit in the mortar joint of the window recess (Figure 3c). These faults easily lead to cracking and crumbling of the render/masonry/concrete, and to consequent leakage. Recommended solutions are shown in Figures 3b and d. The absence of turn-ups against the window recess is a general problem for all types of facade cladding. Figure 3e shows an example with wood cladding. Such solutions can easily give rise to leakage at the side edges of the flashing and in the worst cases can lead to water ingress behind the wind-barrier layer.

When wood cladding is used, it is essential to leave an air gap between the flashing and the finished-off cladding. End-wood in contact with the flashing (Figure 3e) will facilitate absorption of moisture into the wood, with possible subsequent rot problems. The recommended distance between end-wood and flashing is 6–10 mm (i.e. larger than the size of a raindrop, but smaller than the end turn-up of the flashing) (Figure 3f).

When windowsill or weatherboard flashings are being fitted below the underside of the windowsill without a turn-up, water will be led into the structure. A design with a groove in the front edge of the windowsill does not offer satisfactory tightening against rain or moisture. An example of recommended design beneath a windowsill is shown in Figure 3f.

Figure 3a Unsatisfactory rendering around windowsill flashing causing cracks. Source: Norwegian Building Research Institute, Oslo

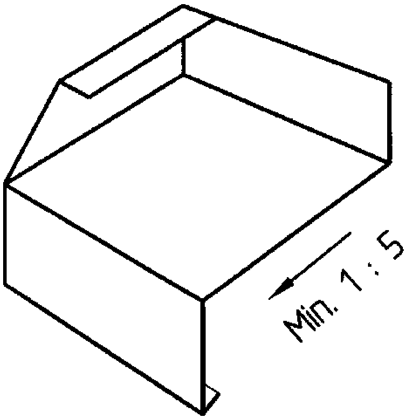

Figure 3b Recommended design of windowsill flashing against a rendered facade

Figure 3c Point of leakage due to the absence of flashing turn-up against a window recess. Source: Norwegian Building Research Institute, Oslo

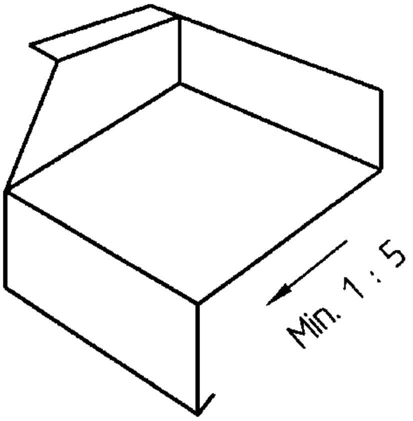

Figure 3d Recommended design of windowsill flashing against brick masonry

Insufficient slope away from window can exert water pressure against joints and transitions to adjacent building components. A slope of minimum 1:5 downward and outward from the window is normally recommended (Figure 4).

Figure 3e Poor solution where the wood cladding is brought into contact with the windowsill flashing. In addition, the end turn-up is missing. Source: Norwegian Building Research Institute, Oslo

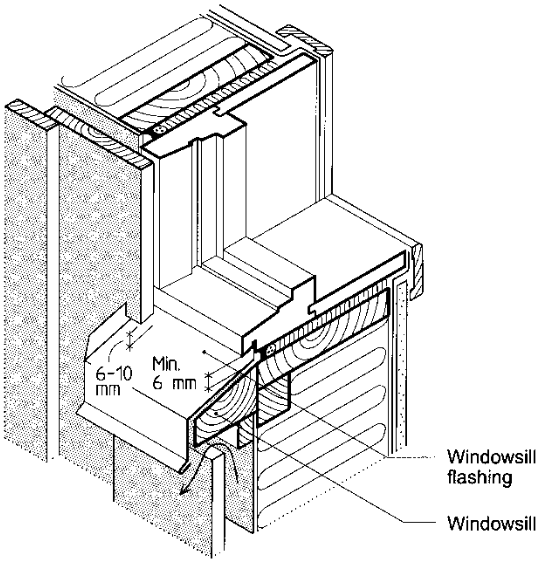

Figure 3f Recommended design of windowsill flashing against wood cladding

The jointing of long windowsill or weatherboard flashings must be designed so that the flashing can absorb thermal expansion/contraction and remain watertight. Jointing with short overlapping as the only safeguard often results in water penetration. The use of folded welts generally ensures watertight joints, as well as accommodating thermal expansion or contraction (for the recommended solution, see Figure 5).

Gable, parapet and transition flashings

The parapet is generally one of the construction details that is most exposed to wind loads. To prevent ingress of rainwater behind the flashing or to stop the flashing from being blown off, great care has to be taken with both design and installation. Several damage conditions experienced with gable, parapet, balustrade and

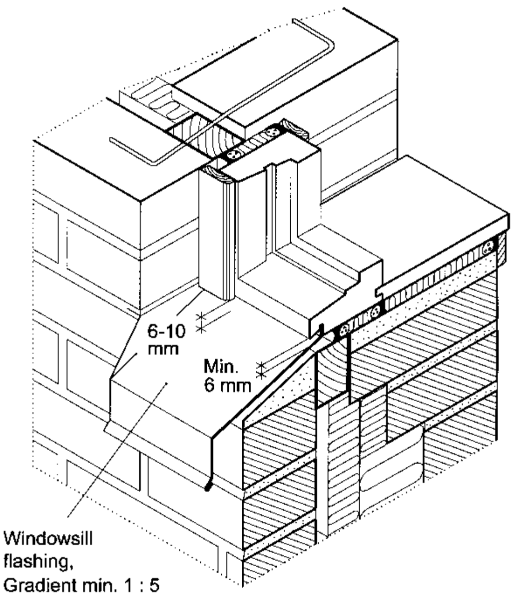

Figure 4 Recommended design of a window installation in the outer side of a cavity wall

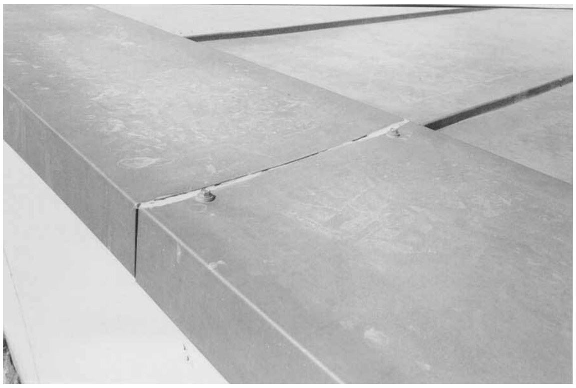

Figure 6a The top of the parapet is formed as a 'gully'. Overlap joints and nailing of the flashing from above render the structure prone to leakage. Sealing solely with mastic is not effective in the long term. Source: Norwegian Building Research Institute, Oslo

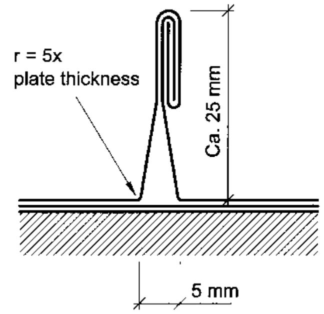

Figure 6b Jointing of parapet flashing with double-raised welts (i.e. a double standing seam), and with possible sealant in the welt, provides a watertight joint

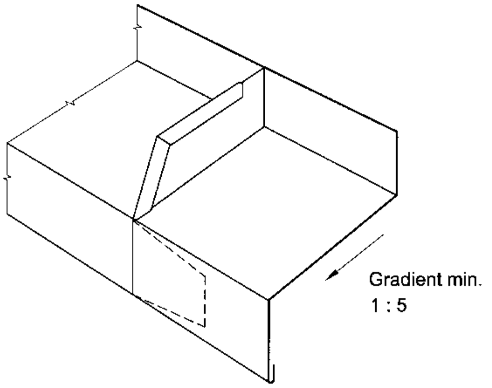

Figure 5 Recommended jointing of windowsill flashing. Jointing must be located between the windows

transition flashings also apply to balcony and top flashings, as well as flashings around ventilation louvres. Balcony and/or balustrade flashings are often penetrated when antennas, sunroofs, windshields, etc. are installed. Such devices should be fastened to the in- or outside of the parapet/balustrade without perforating the flashing or, alternatively, furnished with grommets and/or collars.

The most common fault with regard to parapet flashing is the design of the jointing. Overlap jointing, often combined with nailing of the flashing at the top edge, can easily lead to leakage (Figure 6a). Few problems have been registered whenever welts have been employed (Figure 6b). Folded joints (welts) incorporating a sealant are water resistant and permit thermal expansion/contraction.

Parapets and gables with elevated projections of varying widths can provide challenging tinsmith work. With parapet projections, it is vital that flashings and roofing are formed in such a way that the sealing is not damaged.

To diminish the visual impact of the parapet flashing, it is common practice to reduce the turndown along the facade. Too short turndowns make it possible for wind to blow water in under the flashing. The parapet flashing for multi-storey buildings should be drawn down a minimum 150 mm along the facade (Figure 7).

Parapet flashings should act as outer rain barrier in a two-stage tightening, i.e. there must always be a tightening layer behind the parapet flashing. When the tightening layer under the flashing is missing, water ingress can easily arise. Also, in cases where the roofing material has not been drawn across the parapet under the flashing, water can enter under

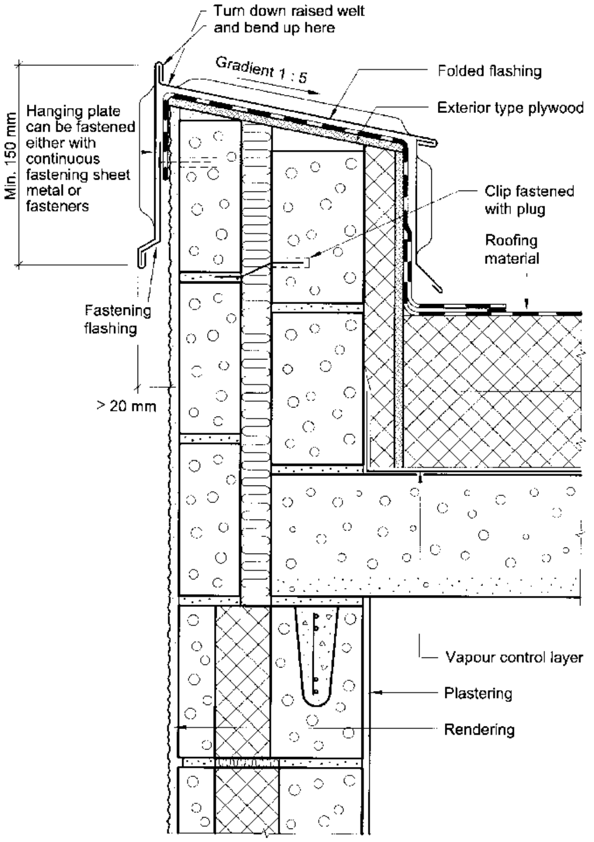

Figure 7 Example showing the recommended construction of welted parapet flashing

the flashing (on the facade side) resulting in leakage behind the wind barrier. A recommended solution is shown in Figure 7. Fastening at the inward edge of the parapet must be positioned a minimum 150 mm above the roofing material in order to prevent leakage due to static water on the roof. This in turn necessitates a parapet that is not too low.

When the turndown along the facade is finished off against the wall waist, rain striking the parapet is led directly in towards the facade. Depending on the facade material, this moistening can lead to staining and frost damage (Figure 8). Norwegian Standard 3420 stipulates finishing off a minimum 20 mm away from the wall waist. Among other factors, the necessary distance from wall waist depends on the height, form and location of the building.

The parapet should always have a minimum 1:5 slope inwards towards the roof surface. An inwards incline reduces the danger of ice and/or snow sliding off the parapet. In addition, the slope is an important safeguard against static water, snow and/or ice and thereby water pressure on joints in the parapet flashing.

Figure 8 Finishing-off of the parapet flashing against the wall face has led to wetting/moistening of the facade with consequent organic growth. Source: Norwegian Building Research Institute, Oslo

Wall flashing details

The junction between the roof and adjacent, upper outer wall is a vulnerable point. For wood frame walls, the transition must be designed by finishing the roofing underneath the wind-barrier layer within the wall (Figure 9a). Leaks can easily arise whenever the wind-barrier/roofing material overlap is missing, even when the flashing is installed as a rain shield. The most frequent cases of registered damage are for masonry and concrete walls. A typical fault is flashing not being inserted in the mortar joint (notch), or where the insertion joint has become so jagged and uneven that water can run in behind the flashing. In the case of cavity walls, one must always expect water penetration through the external face of the wall. Drainage water must therefore be drained away as shown in Figure 9b. Connection of flashing to concrete walls is shown in Figure 9c.

Ridge and bevel finishing

The type of ridge flashing should be selected according to the type of roofing material and the local climatic

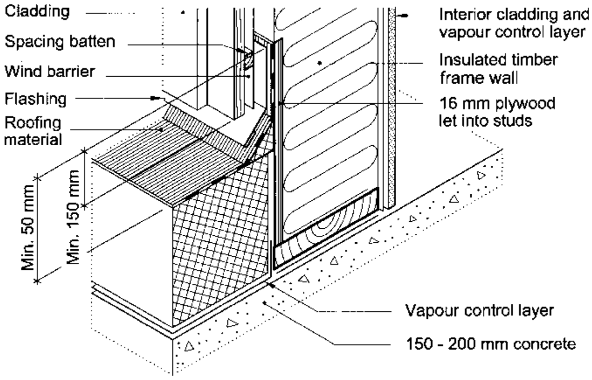

Figure 9a Recommended design of roofing against a wood frame wall

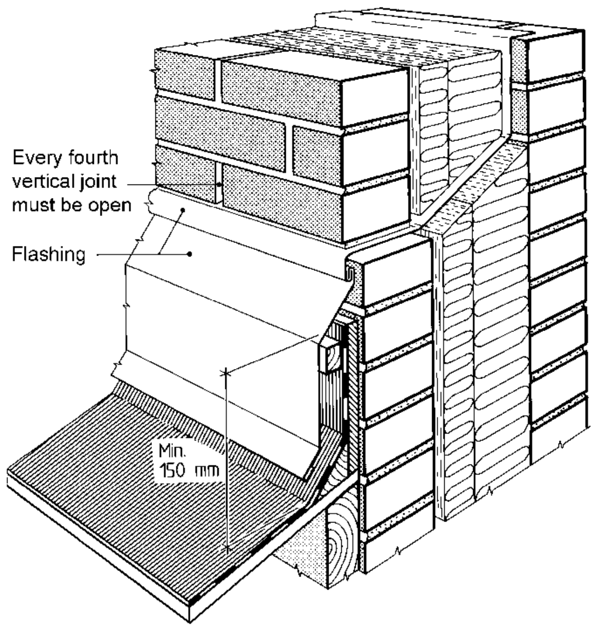

Figure 9b Flashing detail at a roof/cavity wall junction

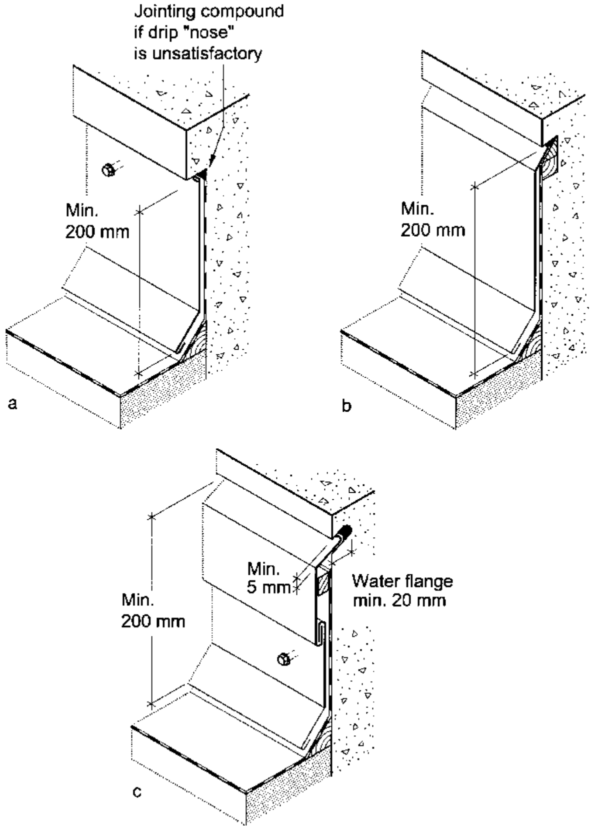

Figure 9c Recommended designs of a connection to a concrete wall. Variant (c) is evaluated as being the safest against water ingress

conditions. Ridge flashing must be designed and fastened so that it will withstand the local wind loads. Heavy wind loads on the roof ridge may also blow rain and snow in under the flashing. Achieving the necessary ventilation in the ridge of a ventilated roof, while at the same time preventing the ingress of rain and snow, makes great demands on both design and workmanship. Detail solutions depend on the type of roofing employed. Figure 10 shows an example of a ridge design that provides for the ventilation of large roof areas while preventing the intrusion of rain and snow.

Chimneys and other openings in roofs

Sealing around chimneys and other openings in roofs can be difficult. As for flashings in general, it is important that the flashing should not be the sole tightening layer, but should primarily act as a rain barrier. Moreover, where openings pass through a roof, the flashing will protect the sealing layer underneath against mechanical loads exerted by snow and ice. As a rule, a fully clad chimney is the safest solution with regard to water leakage and should always be used in the most exposed/unsheltered areas. In Norway, exposed or unsheltered areas usually means coastal and fjord areas northwards from the South and West of the country, as well as cold and windy inland areas in South and North Norway.

The sealings of openings in roofs or walls are vulnerable points, even when a separate tightening layer has been installed beneath the flashing. Figure 11 shows a case of damage due to the flashing end not being inserted deep enough into the notch of a brick

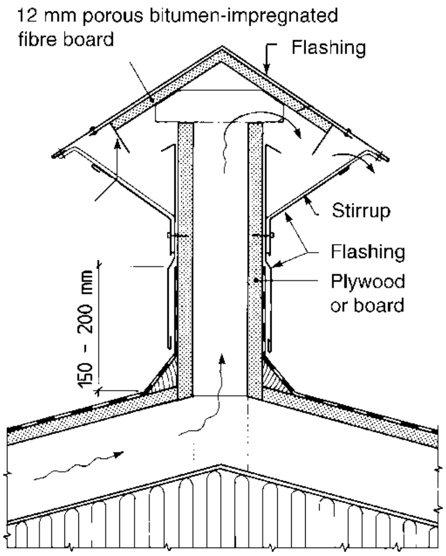

Figure 10 Continuous, longitudinal ventilation louvre along the ridge of an insulated, ventilated pitched roof. Source. NBI (2000)

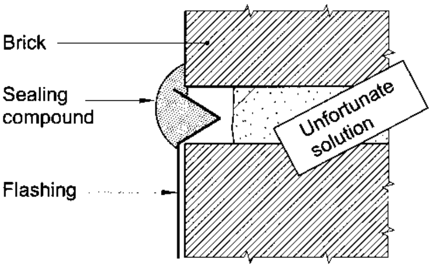

Figure 11a Poor solution for a flashing connection to masonry. Weathering of the sealing compound will gradually allow water to penetrate behind the flashing

chimney. A superficial jointing compound will never provide an effective sealing in such a case. Flashings that are to be inserted into a slit or notch should be designed with a water flange (Figure 11b). In the case of pipes and ventilation shafts, where it is impossible to finish off flashing in a notch, it is common practice to use a flange/collar.

Leaks frequently occur because work has been abandoned in a half-finished state. In the case shown in Figure 11c, a top flashing is missing. A recommended solution is shown in Figure 11d. Another culprit when it comes to leakage points at openings are the corners of a chimney flashing. Again, the use of folded welts is the preferred method of executing corners (Figure 12). Chimney flashing joints should not be executed with overlapping joints.

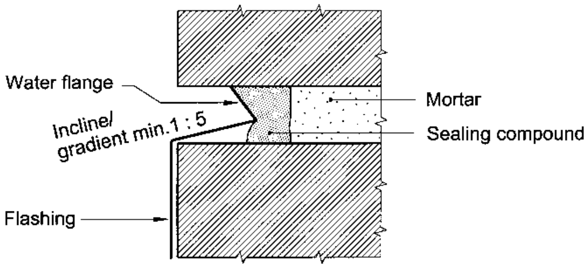

Figure 11b Flashing inserted in a notch with a water flange. The notch should be a minimum of 5 mm high and 20 mm deep

Figure 11c Collars without protective flashing can give rise to severe leakage. A perforation in the flange transition, as in this case, makes the situation even worse. Source: Norwegian Building Research Institute, Oslo

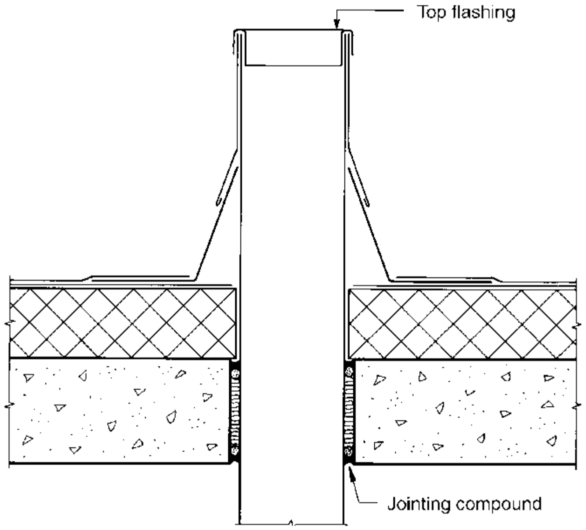

Figure 11d Example showing completed roofing-in of a pipe. Source: NBI (1991)

Gable, abutment and valley gutters

Few problems with gable, abutment or valley gutters have been registered. Most of the problems are

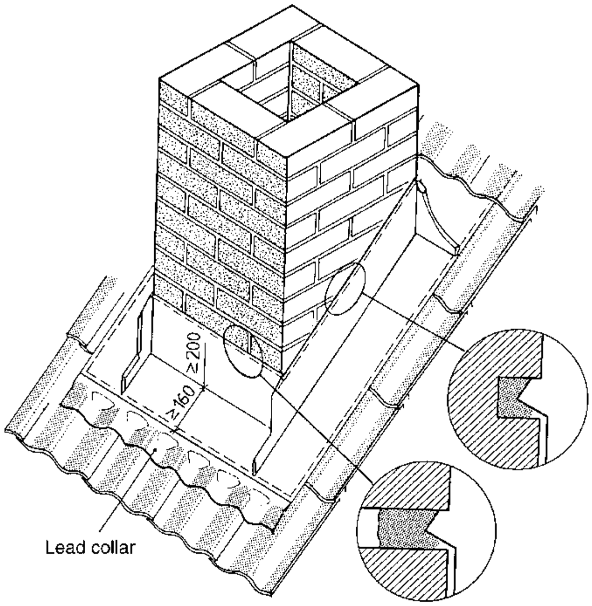

Figure 12 Recommended design of foot flashing for a brick chimney in sheltered areas

related to broken roofing tiles, especially in connection with valley gutters. Short overlapping at jointing has resulted in cases of leakage. The same applies when the under flashing is missing. Another typical problem is the tendency to use too narrow widths on both valley gutters and abutment gutters. Experience has shown that a width of 50 mm on abutment gutters is too narrow.

Recommendations for further work

The work presented here is embedded within the ongoing NBI Research & Development Programme 'Climate 2000' (Lisø *et al.*, 2004). The present authors' ambition is to use the results from the present investigation as a tool for further studies on the performance of weather-protective flashing in severe climates. Building damage records in NBI's archives reveal serious deficiencies in the construction industry when it comes to knowledge concerning the planning, design and construction of weather-protective flashing. The investigation presented here has revealed a number of typical problem areas. The results will be used as a basis for planning new field studies and laboratory investigations.

The field study will be undertaken as the basis for a systematic review and assessment of various forms of flashing design. The study will be carried out in close cooperation with the construction industry.

The laboratory investigations will be carried out to analyse how various types of weatherboard flashing can provide a shield against precipitation. The test arrangement will encompass techniques that are expected to be good, average and possibly deficient/unsatisfactory. The tests will be carried out in a turnable equipment for full-scale rain and wind tightness testing (RAWI box). The main objective will be to obtain a basis for the ranking of different flashing designs according to their performance in different climate situations.

Conclusions and implications

The transition from a prescriptive to a performance-based building code in Norway has strengthened the demand for supporting standards and easily accessible design guidelines and best-practice solutions. The widely recognized NBI Building Research Design Sheets comply with the requirements in the building code, and their main purpose is to provide solutions and recommendations that encourage high quality in the planning, design and construction of buildings in a country with an extremely variable climate. The presented investigation of NBI's project archives reveals serious deficiencies in the construction industry with regard to knowledge about the correct design and construction of weather-protective flashing, illustrating the need to obtain further knowledge on commonly used flashing solutions. The presented analysis clearly shows that certain faults and deficiencies are recurring items. Windowsill/weatherboard flashings comprise as much as 41% of the examined building damage cases associated with weather-protective flashing. Damage in connection with parapet flashing comprises 27% of all cases included in this investigation. With few exceptions, instances of damage are on Norway's coastal areas.

The presented analysis calls for a redefinition and strengthening of existing performance requirements for weather-protective flashings in severe climates as a basis for the improvement of existing flashing design, guidelines and workmanship. Flashing should always be designed and performed so that water is directed away from the structure, and rain or snow is not led underneath the flashing with the consequent risk of leaks. Generally, a flashing should not be the only tightening layer against water ingress. Flashing should function primarily as a drainage covering or external rain screen in a two-stage tightening (Figure 13). It will also act as a mechanical safeguard for any underlying barrier layer, e.g. roofing. The flashing and underlying structure must always be designed so that any possible water entering behind the flashing will not penetrate the structure behind.

Simplified flashing solutions could be acceptable in areas with low and moderate driving rain exposure. However, the economic benefit from such simplification is marginal. In light of a more severe climate in parts of the country due to global warming, or rather the uncertain risks of future climate change, it would be a fairly inexpensive insurance to choose flashing solutions with a higher climatic safety level.

The results from the investigation, revised and improved high-performance flashing solutions for typical problem areas, will be incorporated in the appropriate Building Research Design Sheets.

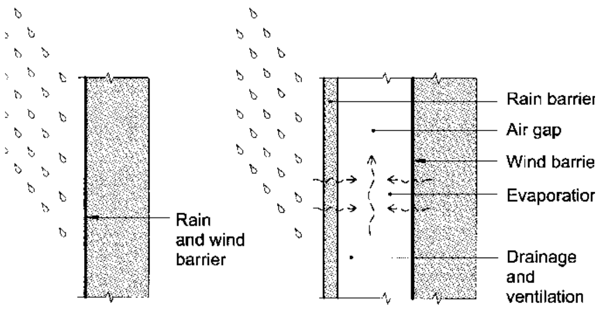

Figure 13 Principle of one-stage tightening (left) and two-stage tightening (right)

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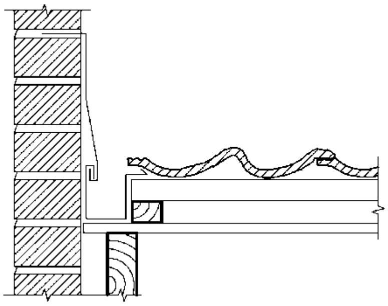
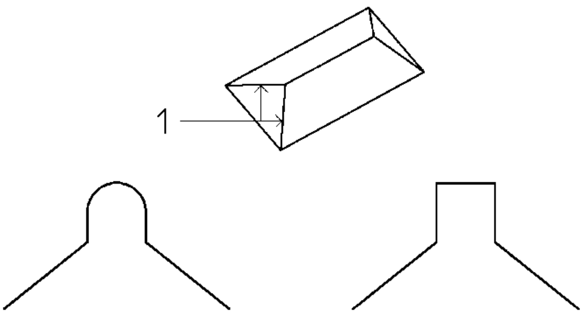
Appendix: Definitions

The original Norwegian definitions used in this paper comply with the terms and definitions given in Norwegian Standard 3420 (1999). The following corresponding English equivalents have been used throughout.



Abutment gutter

A roof gutter that follows the slope of a roof (e.g. a gutter for leading water into or away from a surface where the roof surface abuts the roof edifice or chimney) (see above), as well as a gutter compensating for the height difference in roof surfaces or coverings, or between differing coverings. A gable gutter is a typical abutment gutter.



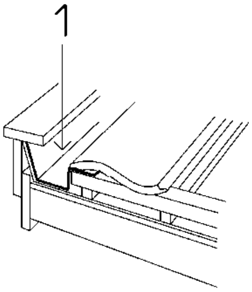
Bevel flashing

A flanged sheet metal covering (see the examples above) that protects the bevel (1) on a roof, e.g. a hipped roof.

Fastening flashing

A flanged sheet-metal covering used to fasten the main flashing in order to achieve a concealed fastening and to avoid perforating the main flashing.

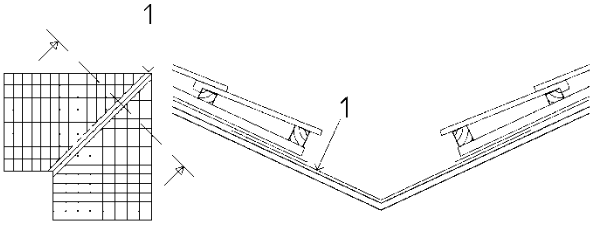
Gable flashing
A flanged sheet metal covering that protects the upper side of a gable wall.



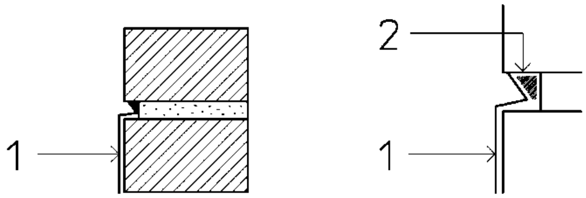
Gable gutter
A gutter (1) that abuts gable (see above).

Parapet flashing
A flanged sheet metal covering that protects the top (and possibly sides) of a roof parapet.

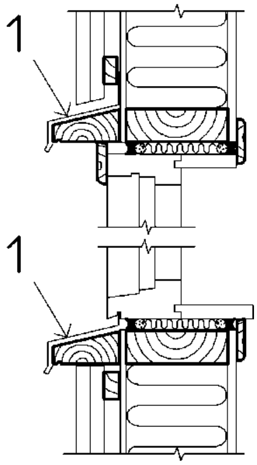
Ridge flashing
A flanged sheet metal covering that protects a roof ridge.



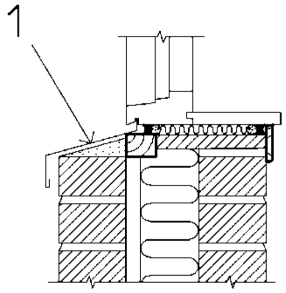
Valley gutter
An inclined valley gutter (1) between adjacent, sloping roof surfaces (see above).



Water flange
A bend in the inclined flashing (1) to facilitate insertion of the flashing into a horizontal notch (2), with a reverse bend to prevent water running underneath the flashing (see above).



Weatherboard flashing
A flanged sheet metal covering (1) that conceals the weatherboard over openings in walls (e.g. over and under windows) (see above).



Windowsill flashing
A flanged sheet metal covering (1) that covers the lower side of an opening in walls (e.g. under windows) (see above).

Climate adapted design of masonry structures

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Abstract

Empirical data on the design and performance of masonry buildings in Norway is presented, based on a comprehensive analysis of 302 process induced masonry defect assignments in the 20-year period 1983-2002. Masonry structures are considered "maintenance-free" if properly designed and constructed, and when located in dry climates with low driving rain exposure. However, solutions for a sheltered inland climate are not necessarily appropriate in more exposed climates. It is therefore of utmost importance to establish the most significant challenges concerning design of masonry structures in harsh climates. The results are a first approach towards improved design guidelines for climate adapted masonry structures.

Keywords: brickwork, building defects, building envelope, building pathology, building performance, building stock, climate adaptation, climatic impact, durability, masonry, moisture, Norway

1. Background

1.1. A brief historic overview

Brick and masonry walls dominate the visual landscape of the built environment in most European countries. Experience-based knowledge gained over the last few centuries has established masonry walls in relatively dry climates with low driving rain exposure as reliable and durable building envelopes.

In the Scandinavian countries wood are the most common building material, and also the most common cladding material for domestic buildings in Norway – due to easy access to wood. External walls below ground level have, for domestic buildings, traditionally been carried out in LECA masonry (Light Expanded Clay Aggregate), particularly widespread in the period 1960-1990. There are few masonry houses in Norway older than 200-250 years. Most of them are to be found in cities like Oslo, Bergen, Trondheim, Kristiansand, Stavanger and Ålesund. There are also rather few masonry buildings in the three northernmost counties of Norway. Nevertheless, masonry has a long-established and natural place also in Norwegian building traditions.

Legislation and building regulation has undoubtedly had a major influence on the historical development of masonry structures in several European countries from the middle age until the beginning of the 20th century, great city fires being one of the most

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important drivers for change. In retrospect, it looks as though extensive city fires entailed a mental change amongst the citizens, as they were willing to accept restricted proprietary rights. ”Murtvangsloven" (“the Brick Restraint Act” of 19 May 1904), prohibiting the erection of wooden houses in Norwegian cities, represented a considerable intermezzo in the debate on building regulation and was at that time perceived as a change of paradigm. The traditional dense built Norwegian wooden cities were virtually given a deathblow. The formidable fire in Ålesund in the same year (one of the most severe fire catastrophes in Norway through the ages) accelerated the enforcement of the Act.

Today, masonry in Norway is primarily employed in large buildings (e.g. office and enterprise buildings and apartment buildings). However, several years of persistent marketing from masonry manufacturers and contractors have produced the intended result, as there is also now an increase in the use of masonry in domestic building. Leca (owned by maxit Group, a part of the German company Heidelberg Cement), the largest manufacturer of masonry units, in co-operation with several prefab house manufacturers, has recently developed a catalogue of small masonry houses. Masonry houses are being marketed as virtually “maintenance-free” buildings, as opposed to wooden buildings where one according to Norwegian television commercials are subject to a slave-like dependence on the bucket of paint.

1.2. International research focus

Even though masonry structures are normally considered “maintenance-free”, if properly designed and constructed, they are undoubtedly vulnerable to damage and defects in harsh climates with high frost and driving rain exposure. It is therefore of utmost importance to recognize the most significant challenges concerning design of masonry structures in severe climates in order to establish research and education efforts. Analyses of building defects should form part of approaches aimed at revealing these challenges.

Research work presented at the latest international masonry conference, “13th International Brick/Block Masonry Conference” [1], forms a clear picture of high-priority research areas for masonry research. About half of the 143 papers presented at the conference dealt with mechanical properties or mechanical behaviour of masonry, while durability, material properties or material behaviour influenced by moisture was the main focus in a mere 15% of the papers. The same bias was also apparent at the “6th International Masonry Conference” in London two years earlier [2]. Scientific studies of masonry defects are almost absent in international journals.

1.3. Objective and scope

This paper presents challenges concerning design of masonry structures under severe climatic conditions, based on lessons learned from two decades of process induced building defect investigations. First, results from a review of 302 building defect assignments related to masonry in the 20-year period 1983-2002 are presented. Next, a case study of flaws and defects revealed as part of a comprehensive investigation carried out ahead of the rehabilitation of His Majesty the King’s Guard Huseby Barracks is provided. Finally, lessons to be learned and implemented in the future design of climate-adapted masonry structures are discussed.

2. Masonry defects in Norway

2.1. Source and method

SINTEF Building and Infrastructure's archive of process induced building defect assignments represents one of Norway's most important sources of knowledge on types of building defects and related causes [3] [4]. SINTEF Building and Infrastructure has undertaken analyses of building defects for more than five decades, both on behalf of the construction industry and in comprehensive field investigations. General information on these assignments is filed in the institute's central archive, and registered electronically.

Ingvaldsen [5] defines "process induced building defects" as absence or reduction of presupposed capacity that is discovered after a construction project has been completed and taken over by the owner, and which he demands to be repaired. Thus, process induced building defects bring about exceptional maintenance costs, i.e. cost that should not have been incurred – or additional costs related to more frequent maintenance than forecast. This is because the actors involved have not succeeded in fulfilling the requirements of standardised or generally recognised methods or specifications. Defects caused by normal wear and tear are not defined as building defects. The same goes for damage due to fire or natural damage, damage which is not included in this definition.

The expensive lessons learned described in the previous section should be employed to good purpose in new building. Altogether it is found that SINTEF Building and Infrastructure has more than 5,000 process induced building defect assignment reports in its archives [3] [5]. The ongoing establishment of the archive allows for in-depth analyses of causal relations of different types of building defects on a wide variety of building envelope elements. Results from a comprehensive investigation of the paper copies of 302 process induced building defect assignment reports inflicted on masonry structures for the 20-year period 1983-2002 are presented in this paper, adopting the definition above (in the following referred to as "process induced masonry defects").

2.2. Results

Defects related to the building envelope constitute about two thirds of the about 2000 investigated cases in the 10-year period 1993-2002 [3]. Defects related to external walls above ground level constitute 29% of the cases (see Fig. 1), about half of these related to masonry structures. Moisture as the main source causing the defect accounts for as much as 76% of all investigated cases. Many types of building defect cases are recurring items, which indicate a general lack of knowledge amongst the different actors in the construction industry concerning fundamental principles of building physics [3].

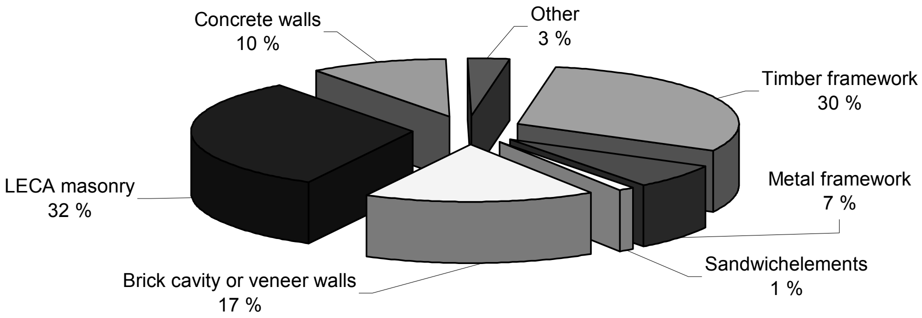
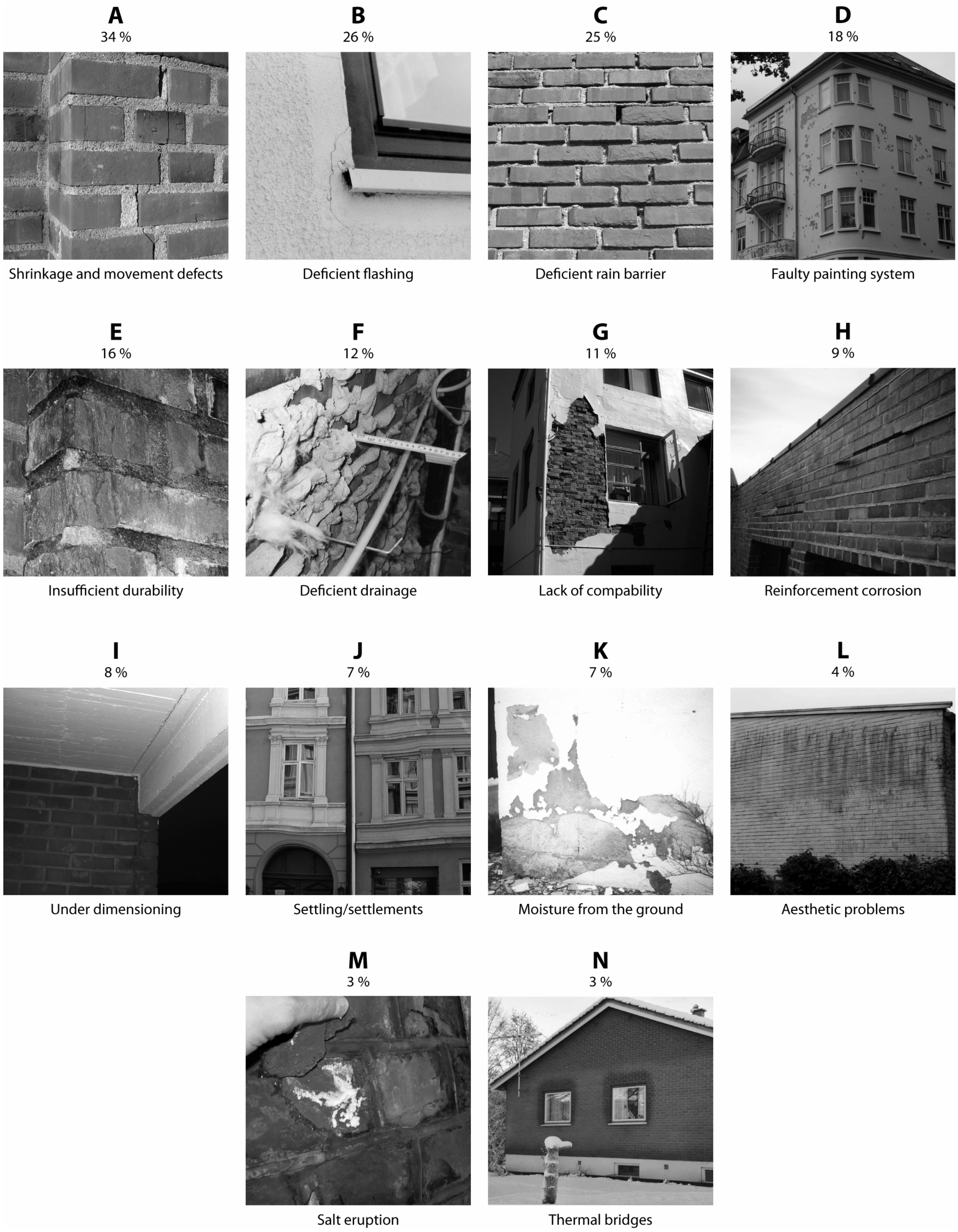


Fig. 1. Process induced building defect cases for the 10-year period 1993-2002 (a total of about 2000 building defect cases), distributed by type of external walls above terrain [3].

Table 1. Process induced building defects inflicted on masonry structures (302 building defect assignments related to masonry in the 20-year period 1983-2002). Categories of causes of defects are distributed by frequency according to the percentage of building defect cases associated with the main cause of defect (see Fig. 2 for illustrations)

Main cause of defect		Explanation
A	Shrinkage and thermal movement defects (34%)	Movement joints missing, absence of sliding layer between masonry and foundation, concentrated tension loadings, locking of masonry to other structures
B	Deficient flashing (26%)	Deficient door/window/parapet flashing, faulty drainpipes and roof gutters, faulty door/window installation
C	Deficient rain barrier (25%)	Non-watertight/ porous mortar joints or disintegration of the surface, faults in composure of the rendering
D	Faulty painting system (18%)	Unfortunate choice of paint, paint that is too vapour tight
E	Insufficient durability of masonry units (16%)	Low frost resistance of bricks and mortar, sulphate attack on block
F	Deficient drainage of the wall (12%)	Too narrow air-gap, mortar bridges between outer leaves and rear wall, missing drainage opening at bottom of wall
G	Lack of compatibility (adhesion) (11%)	Inadequate adhesion rendering/substructure, lack of compatibility mortar joints/masonry units
H	Reinforcement corrosion (9%)	Corrosion on reinforcement
I	Under dimensioning (8%)	Anchorage to rear wall missing, insufficient bearing capacity, earth pressure, overload
J	Settling/ Settlements (7%)	Settling defects, soil mechanics
K	Moisture absorption from the ground (7%)	Raising damp, capillary action, deficient drainage
L	Aesthetic problems (4%)	Organic growth, unsatisfactory colour and structural variations, efflorescence of salts (not causing defects)
M	Salt eruption (3%)	Crypto-efflorescence of salts causing scaling of rendering or bricks/blocks
N	Thermal bridges (3%)	Heat loss, condensation, staining, discolouration

Process induced building defects inflicted on masonry structures are presented in Table 1, and illustrated in Fig. 2. The masonry defects are grouped according to a system developed as part of the examination. Main categories of causes of defects are in Fig. 2 distributed by frequency according to the percentage of building defect cases associated with the main cause of defect (thus, the percentage of defects do not add to 100%). Shrinkage and thermal expansion/contraction without the necessary countermeasures are the most common cause of defect, registered in one third of all cases of masonry defects analysed. Furthermore, the investigation reveals that two thirds of all cases comprise faults in the execution of the actual rain barrier (non water-tight mortar joints and rendering), drainage from the air gap (insufficient air gaps, mortar bridges between outer leaf and rear wall as well as missing drainage openings at bottom of wall) and the execution of window and parapet flashing.



A
34 %
Shrinkage and movement defects

B
26 %
Deficient flashing

C
25 %
Deficient rain barrier

D
18 %
Faulty painting system

E
16 %
Insufficient durability

F
12 %
Deficient drainage

G
11 %
Lack of compability

H
9 %
Reinforcement corrosion

I
8 %
Under dimensioning

J
7 %
Settling/settlements

K
7 %
Moisture from the ground

L
4 %
Aesthetic problems

M
3 %
Salt eruption

N
3 %
Thermal bridges

Fig. 2. Example illustrations of the main defect categories. See Table 1 for explanation.

Fig. 3 presents an analysis on how the main defect categories vary through four 5-year periods. There is a pronounced increase in the number of assignments over the 20-year period. However, a few time dependent trends can be seen. For instance, sulphate attack on LECA blocks (Light Expanded Clay Aggregate concrete, see category E) was a common defect cause only in the first ten-year period. Low frost resistance of new light-coloured clay bricks on the marked constitute the bulk of the increase in defect cases within the last five-year period. The overview in Fig. 2 and Fig. 3 does not differentiate between varying types of masonry. However, the analyses of masonry defect cases in the database reveals that defects induced by shrinkage and thermal movement occur more frequently in LECA and concrete masonry than brickwork. On the other hand, defects associated with non-watertight masonry, reduced durability and reinforcement corrosion are more common in brickwork than in LECA masonry. A majority of causes of defects categorised in Table 1 are related to moisture. Moisture related defects account for as much as 80% of the investigated masonry cases.

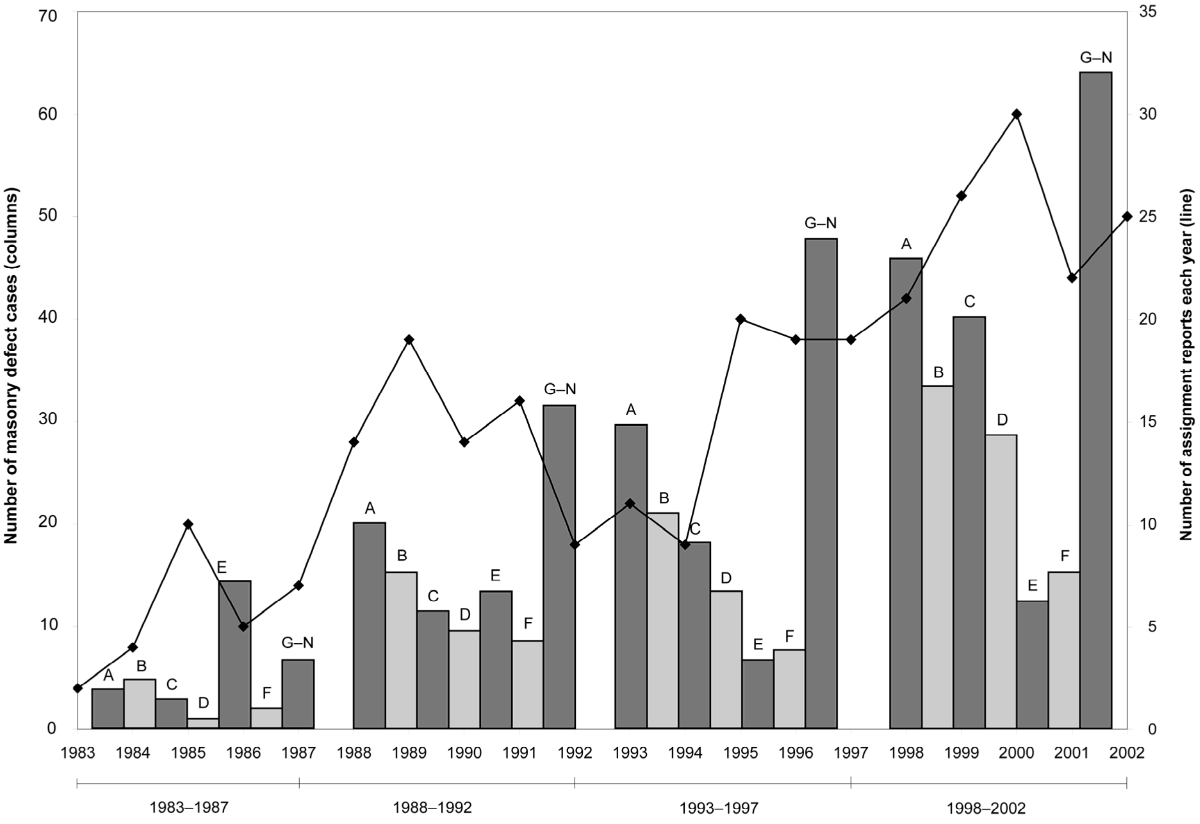


Fig. 3. Variations in main defect categories for four 5-year periods. (See Table 1 for explanation.) Number of masonry defect cases (columns) is given on the left y-axis. Number of assignment reports each year (see line) is given on the right y-axis.

2.3. Evaluation of results

The analysis is based on building defect assignments carried out by SINTEF Building and Infrastructure and do not represent a complete overview of process induced building defects in Norway. A majority of the cases of defects are located in municipalities near SINTEF Building and Infrastructure's offices in Oslo and Trondheim. This is due to SINTEF Building and Infrastructure having easier access to building defect assignments in its vicinity. The inflow of building defect assignment reports to the project archive is based on commercial consultancy assignments from different actors in the construction industry, and thus do not represent a systematic or in any way planned selection of building defect cases. It is therefore important to emphasise that only a small part of the total number of process induced building defects in Norway emerges in the SINTEF Building and Infrastructure building defects archive [3]. One of the major advantages with the archive is clearly the large number of assignments over a long time period. Also, the archive contains thorough descriptions of cause, extent and preventive actions on complex building defect cases, investigated and described by highly competent researchers.

The presented results are in good agreement with a comparable investigation of defects related to concrete in the Netherlands [6], the only corresponding investigation to be found. De Jong [6] based his ranking of defect causes on 650 reported building defect assignments investigated over a 30-year period by his engineering consultancy firm. Restrained shrinkage is topping his list of the most frequent causes of concrete defects, based on the number of defects (and not on the economic consequences). The number of defects is also the ranking criterion for this investigation.

2.4. His Majesty the King's Guard Huseby Barracks – a case study

This section provides results from a thorough case study of defects in one of Norway's largest masonry projects. A large number of classical flaws and defects have been discovered in His Majesty the King's Guard Huseby Barracks (building period 1981–1985, see Fig. 4). The authors have, in close co-operation with the building owner Norwegian Defence Estates Agency (NDEA) and the consulting engineers, revealed major flaws, defects and deficiencies relating to the masonry façades and adjoining structures. The number of building defects unveiled is considerable.

Fired clay brick is used as the principal material in both the façades and interiors of the buildings (suction rate 1.2 kg/(m²·min.). The outer walls are insulated brick cavity walls. The inner leafs are utilised as load-bearing structures for floors and roofs in several buildings, e.g. in officers quarters and caserns. The remaining buildings are constructed with load bearing concrete columns integrated in insulated, non-load-bearing cavity walls. The load-bearing part of floors and roofs consist of concrete. The total floor area of His Majesty the King's Guard Huseby Barracks amount to about 35,000 m^2.

The investigation has revealed the following main defects [7]:

- Frost action damage on bricks. See close-up picture of frost-damaged bricks in Fig. 2, category E.
- Corroded steel reinforcement, see Fig. 2, category H. Picture of a window superstructure with reinforcement corrosion. Reinforcement in mortar joints 1 to 5, 8 and 12 above the window. Bottom course is partially without adhesion to the masonry above.
- Cracks due to unsatisfactory application and performance of movement joints. See picture of a vertical crack at a brick wall "corner" in Fig. 2, category A.
- Lack of ventilated or drained space behind the outer brick leaf and moisture transfer into the inner leaf of the brick cavity walls by way of mortar bridges in the cavities between the brick leafs. See Fig. 2, category F, where excess mortar from the inner leaf is projecting into cavity between the leaves. The outer leaf is dislodged before photographing.
- Disintegrated mortar joints. See Fig. 2, category C, where porous masonry mortar with insufficient water-sealing properties is illustrated.

The outer leaf of cavity walls always has limited protection against rain. Thus, in principle, cavity walls in severe climates must be constructed with two-stage weatherproofing. Efficient ventilation behind the outer leaf has to be ensured in cavity walls in order to avoid the effects of driving rain and of moisture damage and related defects. There will always be a risk of rain penetrating the outer leaf. Hence, a drainage system (cavity spacing) is also necessary to ensure that water penetrating the outer leaf is effectively drained. The cavity walls of the buildings in His Majesty the King's Guard Huseby Barracks were not constructed according to this principle. Only a full replacement of all climate-exposed masonry will meet the requirements for an adequate cavity wall.

NDEA has therefore chosen to replace all brickwork in façades and to replace wall/roof connections, including new roof overhangs, gutters and drainpipes. Replacement of roofing tiles on a large part of the roofs and reconstruction of all wetrooms along with the removal of mould growth and efflorescence of salts also forms part of the refurbishment.

Fig. 4. His Majesty the King's Guard Huseby Barracks, Oslo, Norway. Source: Norwegian Defence Estates Agency (NDEA).

The expensive, extensive and necessary refurbishment described is meant to ensure a new military facility with long lifetime. The project was carried out at a cost of about 40 million Euros (the project being completed in 1985, the cost given in 1985 equivalent). The rehabilitation costs, completed in 2005, amount to more than 17 million Euros (2005 equivalent). The described defects could have been avoided in the first place if the existing Building Regulations and Codes of Practice had been adhered to, and if construction of the project had been more thoroughly supervised by the NDEA.

3. Towards new climate adapted design guidelines

3.1. Introduction

The investigation of two decades of process induced masonry defect assignments shows that it is possible to obtain durable masonry structures even in countries like Norway, with harsh and extremely varied climatic conditions. However, there is a great potential for both improved design and workmanship. The analyses also reveal that the most frequent types of damage and defect surveyed are rather easy to avoid, simply by applying existing knowledge and by being more aware of the local climatic features and trends on the actual site.

Masonry defects can be understood as a function of local climatic impact, choice of materials and matching composition of materials, design and quality of workmanship. The pursuit of durable masonry structures requires an optimal realization of both the climatic exposure and the special features of brickwork. Masonry structures are "maintenance-free" only if properly planned, designed and constructed. Well-functioning methods and solutions for a typical inland climate (weather-protected areas) are not necessarily appropriate in a more severe type of climate. The presented lessons learned are highly relevant also for geographical areas other than Norway, e.g. the most exposed parts of the UK, and is a first approach towards improved design guidelines for masonry structures in harsh climates.

3.2. The two-stage tightening principle

The results clearly illustrate that the employment of the two-stage tightening principle (i.e. separate wind and rain barrier) is crucial in climates with severe driving rain exposure. This is in agreement with the recommendations of Stirling [8]. However, there is a well-established tradition in several European countries with fully filled cavity. Hens et al. [9] suggests that such walls, even with open head joints, can maintain a satisfactory rain protection, dependent on the severity of climatic impact and the combination of materials used. Yet, there exist no distinct guidelines for when and where to use fully filled cavity walls. The development of such guidelines may be based on the methodologies given in BS 5628-3:2001 [10], which do not advise full cavity fill of unprotected masonry on the west coast of Scotland, parts of North West England, much of Wales, and South West England, due to driving rain exposure (according to assessment methods given in BS 8104:1992 [11]).

The investigation indicates that one weephole per meter is sufficient to drain water from cavity trays at the lower edge of cavity and veneer walls in climates with sheltered or moderate driving rain exposure. There should be two weepholes per meter where severe driving rain exposure is expected.

3.3. Position of window

The correct positioning of windows in cavity and veneer walls is important to avoid defects. Windows should be installed parallel to, or flush with, the thermal insulation layer to avoid thermal bridges and subsequent heat loss. As a main rule the turn-up at the rear edge of the weatherboard flashing should rest directly against the cold side of thermal insulation layer. This positioning of the window ensures a low heat loss, a robust rain protection (especially important in climates with high driving rain impact) and a low risk of moisture defects.

The window can be positioned further to the warm side of the wall in cold inland areas with a low driving rain impact, in order to reduce the risk of internal condensation problems. But, in these cases the tightening details around the window must be carefully considered.

3.4. Frost resistance

The frost resistance of masonry depends on a complex set of material properties and on the climatic impact on the material, e.g. [12]. In part due to this complexity frost resistance of brick and rendering mortar is still tested according to rather simple methods given in different international and national standards. There are designated test methods for different countries, but the results presented in this investigation shows that the performance of masonry depends on climatic exposure at the very local level. Annex B of NS-EN 771-1:2003 [13] includes exposure examples for masonry or masonry elements dependent on the design of the construction, i.e. the risk of frost decay in a given climate. However, the climatic conditions are not specified in the standard. Simple climate adapted design recommendations for the use of bricks in the United Kingdom is provided by Hanson Brick [14]. However, a more pronounced relationship between frost resistance and geographically dependent climatic exposure must be established in order to develop improved standards and design guidelines for different climates.

3.5. Masonry mortar

The masonry mortar must be compatible with the suction rate of the brick in order to ensure the highest degree of water tightness possible, to avoid the disintegration of mortar joints and finally to secure the intended load-bearing capacity. The introduction of new types of clay brick in the Norwegian marked has led to problems due to lack of compatibility between the suction rate of the brick and the traditionally used masonry mortar. The Norwegian focus has been on the type of mortar. However, the type of masonry technique applied may eliminate such problems. E.g. in Belgium and in the Netherlands it is customary to scrape off and refill mortar joints with a particular compacted repointing mortar. In Norway brickwork is constructed with fully filled mortar joints, which afterwards are compacted. The different techniques yield diverse rain penetration resistance. Edgell and Haseltine [15] demonstrate the possibility of repointing weak mortar joints to withstand freezing and thawing and gives a draft specification for repointing.

3.6. Shrinkage and movement defects

The performance of movement joints and sliding layers against the foundation, the most frequent cause of defect in the presented investigation, is highly critical. Martens and Vermeltfoort [16] conclude that the rules determining the spacing of movement joints are primarily empirical and consequently often “a mystery”. Such a basis for movement joint design has resulted in quite different national rules. The conclusion of Martens and Vermeltfoort [16], based on an investigation of cracking in façades as well as literature surveys on the shrinkage and temperature deformation of masonry walls, supports the experience gained in Norway. More accurately defined guidelines on how to minimize shrinkage and temperature deformation are urgently required.

3.7. LECA masonry

Light Expanded Clay Aggregate (LECA) masonry needs always to be rendered to ensure satisfactory air and rain protection. Hence, the correct choice and performance of rendering systems is crucial. Such walls have to be built as shell bedded walls (i.e. a wall in which the masonry units are bedded on two masonry mortar strips at the outside edges of the bed face of the units) to avoid capillary suction through the wall via the mortar joints. Details identified with carrying out of flashings, doors and windows are even more important for LECA masonry than for bricks, as LECA masonry walls are often constructed as compact walls without separate wind and rain barriers. It is also essential that the sliding layer (damp proof course) adjacent to the foundation be properly constructed. The distance between movement joints must be smaller for LECA masonry than for bricks, as the moisture movements are much larger for LECA masonry.

3.8. Weather-protective flashings

Flashings must always be designed and constructed so that water is directed away from the structure, and rain or snow is not led underneath the flashing with the consequent risk of leaks [4]. Generally, a flashing should not be the sole protective layer against water ingress. Flashing should function primarily as a drainage covering or an external rain screen in a two-stage weatherproofing. It will also act as a mechanical safeguard for any underlying barrier layer, e.g. roofing. The flashing and underlying structure must always be designed so that any possible water entering behind the flashing will not penetrate the structure behind.

3.9. New rendering recommendations

A three-coat rendering system has to be used to resist heavy driving rain conditions, frequently experienced along most of the extended Norwegian coastline. A two-coat render is not sufficient [17]. The empirical material investigated here confirms this conclusion. The final coat in a three-coat render may be a suitable inorganic coat like silicate paint. Insufficient and inaccurate performance guidelines on how to ensure satisfactory rain protection and how to avoid cracking has always been a problem, and design recommendations need to be further developed to ensure local-level climate adaptation.

4. Conclusions

When correctly designed and constructed, and with due consideration paid to the distinctive features of masonry, few other materials can match its durability characteristics. However, the level of learning amongst the different actors in the construction industry involved in the design and performance of masonry structures varies greatly. Moisture related masonry defects clearly dominate the picture in Norway, largely due to a lack of both understanding and attention in the designing and carrying out of masonry buildings. The large number of simple and recurring defects presented supports the need for a more thorough understanding of fundamentals of masonry structures and building physics. It is also important to facilitate the exchange of knowledge across borders in relation to national distinctive climates and consequences of building defects under different climatic impact. This is of particular importance due to an ever-increasing internationalisation and exchange of labour. Country distinctive or local knowledge is also necessary when developing nationally adapted product documentation in the form of technical approval and certification.

The presented types of defects and causes indicate a need for both new knowledge, and new methods to ensure the employment of existing knowledge. The described defects at His Majesty the King’s Guard Huseby Barracks could have been avoided if the existing Building Regulations and Codes of Practice had been adhered to, and if the carrying out of the project had been more thoroughly supervised. Experience gained from the recently completed rehabilitation represents a valuable example for future learning.

Driving rain and frost action are the principal climatic challenges to be considered in the pursuit of high-performance masonry structures in severe climates. Shrinkage and thermal movement, the most frequent defect category in this investigation, dominate independent of the climatic impact. It is a defect category more dependent on the design and construction of masonry structures. First-class workmanship necessitates a correct moisture level in the blocks when bricked in, and movement joints and the sliding layer (damp proof course) being carefully considered throughout the construction process.

The investigation also discloses the fact that merely small errors or mistakes can bring about major and often irreparable defects or damage to masonry structures. A large part of the investigated cases could have been avoided through more detailed engineering and applied knowledge on existing design guidelines. The investigation finally reveals the need for design guidelines to ensure local climate adaptation, and improved design guidelines on movement joints.

Acknowledgements

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INCREASED SNOW LOADS AND WIND ACTIONS ON EXISTING BUILDINGS: RELIABILITY OF THE NORWEGIAN BUILDING STOCK[1]

By Vivian Meløysund[2,3], Kim Robert Lisø[2,4], Jan Siem[5], Kristoffer Apeland[6]

ABSTRACT: Results from an investigation of snow loads and wind actions on 20 existing buildings in Norway are presented. The objective has been to investigate to what extent existing buildings meet current regulatory requirements relating to safety against collapse owing to snow loads or wind actions. 18 buildings have a utilization ratio of more than 1.0 under current regulations. The new design rules have led to most of the buildings investigated having reduced safety against collapse owing to snow loads and greater safety against collapse owing to wind actions than the regulations now demand. The investigation indicates too low reliability for a considerable number of buildings according to current building regulations, when evaluating the possible consequences of the conclusions in a national perspective. Scenarios for future climate change indicate both increased winter precipitation and increased temperatures, and thus changing the snow loads on roofs. Wind scenarios for the decades to come indicate an increase in frequencies of strong winds in areas also exposed today. Thus, the future reliability of the buildings in these areas could decrease.

CE Database subject headings: bearing capacity, buildings, climatic changes, Norway, reliability, snow loads, structural design, structural safety, wind loads

INTRODUCTION

Background

Large snow loads on roofs during the winter of 1999/2000 led to the collapse of several buildings in northern Norway. The accident at Bardufoss Community Centre, where the roof caved in and claimed three lives, was the most serious of these accidents (Fig. 1). The most important causes of this collapse were a faulty construction of the roof when the building was erected and larger snow loads on the roof than it was designed for.

Earlier, many roof structures in Norway have not been designed to withstand sufficiently large snow loads, from the viewpoint of current design rules. Several roof structures in parts of the country have presumably a so low load carrying capacity in relation to the current design codes that they may

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[1] Preliminary results presented at the Fifth International Conference on Snow Engineering, Davos, Switzerland, July 2004, (Meløysund et al. 2004).

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be in danger of collapse. Table 1 provides an overview of a number of large buildings where snow has triggered or caused significant damage or collapse (Lisø et al. 2000). The summary is not complete, but gives an idea of which types of buildings that are especially vulnerable to damage. The table is based on information from insurance companies and SINTEF Building and Infrastructure. For most buildings, defects during planning or construction have been the most likely cause of damage. In some cases, the damage has resulted from applicable building regulations not being adhered to, or construction at the location not being in accordance with the design calculations. In a few cases, the snow load assumed in the calculations has been lower than the actual loading.

FIG. 1. Bardufoss Community Centre (photo: National Office of Building Technology and Administration, printed with permisssion)

TABLE 1. Cases of collapse as a result of major snow loads

Building	Type of building	County	Built (year)	Time of collapse/ damage
Stongelandet skole	Swimming pool	Troms	1971	2000
Bardufoss Samfunnshus	Community hall	Troms	1965	2000
Lenangen Skole	School	Troms	1970	2000
Målselv	Community hall	Troms		2000
Storvoll Skole	School	Nordland	1990*	2000
Tromsø Tennishall	Sports hall	Troms		2000
Løkenås-hallen	Sports hall	Akershus	1978/ 1996*	1999
Lofothallen	Sports hall	Nordland		1999
Aukra	Industrial facility	Romsdal		1996
Asker Tennishall	Sports hall	Akershus		1994
Drammen	School	Buskerud		1994
Harstad	Industrial facility	Troms		1988
Birkenes-hallen	Sports hall	Aust Agder		1987
Svelvik Karosseri	Industrial facility	Vestfold		1987
Epokehallen	Drill hall (military facility)	Troms	1982	1983
Tromsø	Industrial facility	Troms		1975

* Year of rebuilding or reconstruction.

The hurricane (Beaufort number 12) which occurred in northwest Norway on New Year's Day 1992 caused damage to buildings costing somewhere in the region of $ 200 million. Wind velocities of 62 - 63 m/s were recorded, the highest wind velocities ever recorded on mainland Norway. The bulk of the damage was related to roofs and roofing, primarily due to insufficient anchoring. Most of the damage that appeared could have been avoided if the existing building regulations and Codes of Practice had been adhered to (National Office of Building Technology and Administration et al. 1993). Investigations into the damage taking place in 1992 showed that during the period 1950-1991 the likelihood of structures in new buildings having too low load carrying capacity was increasing. The investigations also demonstrated that if the safety levels in the regulations were to be conformed to, it would be necessary to update the wind action provisions. 55 % of the recorded cases of damage caused by the hurricane in northwest Norway in 1992 involved buildings erected before 1970 (National Office of Building Technology and Administration et al. 1993). The fact that a building has served well for many years is thus no guarantee that it will withstand subsequent hurricanes.

Principal objectives and delimitations

The principal objective of the investigation has been to obtain a reliable indicator as to whether existing buildings in Norway meet current regulatory requirements concerning safety against collapse owing to snow loads and/or wind actions, and also to establish a basis for the analysis of future climate change impacts on the Norwegian building stock. The analysis encompasses design documentation investigations and field studies of 20 existing buildings in five high-snowfall and five high-wind municipalities in Norway (Siem et al. 2003; Meløysund et al. 2004). Statistical data for e.g. building types, year of construction and geographical localization of the approximately 3.7 million registered buildings in Norway are available in the Ground Property, Address and Building Register (GAB). Special attention has been paid to exposed types of buildings, and the buildings have been randomly selected within the exposed building categories. Assessments of whether the regulations are satisfactory, and theoretical parameter studies of the regulations, are not included in the investigation. The investigation focuses on assessing the buildings' main load-bearing structures and, to a lesser extent, their secondary load-bearing structures.

BUILDING REGULATIONS AND DESIGN CODES

The development of design codes for snow loads and wind actions

The building regulations of 15 December 1949 (National Office of Building Technology and Administration 1949) referred to a general snow load on roofs corresponding to 1.5 kN/m^2. This value could be reduced or increased by the individual building authority with the Ministry's approval. The importance of the shape of the roof for the size of the snow load on the roof was calculated in a simple way. Structures should normally be designed for a wind pressure equal to 1.0 kN/m^2, while a wind pressure equal to 1.5 kN/m^2 should be used in exposed areas. In heavily exposed areas, building authorities could increase these basic values with the Ministry's approval. The sum of the wind shape factors for lee and windward walls for a closed building was 1.2 (i.e. 1 + 0.2).

In NS 3052 (Standards Norway 1970) snow maps were introduced showing zones with roof snow loads with values of up to 1.5 kN/m^2, between 1.5 and 2.5 kN/m^2 and above 2.5 kN/m^2. Four curves for the wind pressure were introduced: the curves A, B, C and D as seen in Figure 2. The code quoted many more detailed rules for the wind shape factors than the building regulations of 1949. The sum of the shape factors for the lee and windward walls was in the code also set to 1.2 (i.e. 0.7 + 0.5). Compared to the building regulations of 1949, the changes in NS 3052 largely implied a reduction in the wind velocity pressures in exposed areas. In NS 3052 the partial factor method was introduced. The partial factor for snow loads was set to 1.6 while the partial factor for wind actions was set to 1.5.

In NS 3479 (Standards Norway 1979) the section dealing with snow loads contained a direct translation of ISO 4355 “Snow loads on roofs”. Characteristic snow loads on the ground for each municipality (5-year return period) with values largely between 1.5 kN/m^2 and 3.5 kN/m^2 were inctroduced. In the case of roofs from which snow was difficult to clear, a return period of at least 20 years needed to be accounted for. The code quoted snow shape factors for a number of typical roof shapes. As a result of the hurricane that struck northwest Norway on New Year’s Day 1992, two new wind curves were introduced for a selection of coastal municipalities in a revision of NS 3479 (Standards Norway 1994): curves E and F (see Fig. 2). The partial factor for wind actions was set to 1.6.

In NS 3491-3 (Standards Norway 2001) characteristic snow loads on the ground with a 50-year return period was specified. The bulk of the municipalities now had a value for snow loads on the ground of between 3.0 kN/m^2 and 4.5 kN/m^2. A few coastal municipalities had values as low as 1.5 kN/m^2, and in some inland municipalities values of up to 9.0 kN/m^2 were introduced. Pitched roofs, shed roofs and curved roofs have also undergone certain changes associated with the shape factors.

In NS 3491-4 (Standards Norway 2002a) a classification of the whole country has been carried out so that wind exposure for all 434 municipalities is defined. Exposure is defined by means of a reference wind velocity (varies between 22 m/s and 31 m/s). Roughness of the terrain in an area 10 km against the wind direction is important for the wind pressure (in this code called the gust velocity pressure). The code defines five such categories of terrain roughness. Other parameters of importance for the gust velocity pressure are the wind direction, the height of the building site above sea level and the topography.

In this regulation amendment process, NS 3490 (Standards Norway 1999) prescribes a 50-year return period for environmental loads. The partial factors for environmental loads are set to 1.5. A reduction factor k_L (with a value of 0.8 – 1.0, depending on the reliability class) by which the partial factor must be multiplied is also introduced.

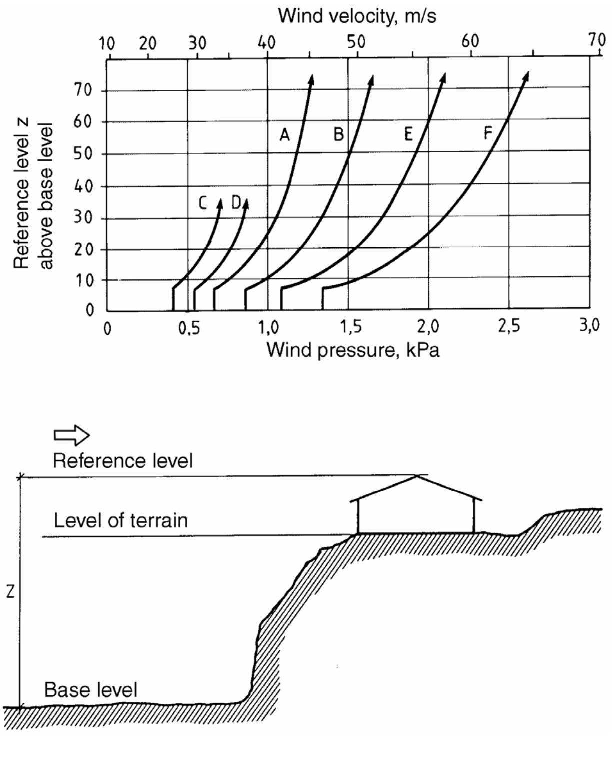

FIG. 2. Wind pressure curves for non-exposed areas (A), exposed areas (B), dense-built environments in non-exposed areas (C), dense-built environments in exposed areas (D) and especially exposed areas according to specification in code (E and F) (figure from NS 3479/A1; Standards Norway 1994, printed with permission from Pronorm AS 02/2006)

The extensive revisions of the codes have increased the level of detail in the regulations considerably. The objective is to achieve a safety level in accordance with Table 2. In other words, the intention is to achieve a more uniform safety level for buildings that have the same reliability class even if they are built in different places, and also to obtain different safety levels for structures classified in different reliability classes.

TABLE 2. The link between reliability class, failure consequences, reliability index and maximum annual probability of failure

Reliability class	Consequence (examples of construction)	Reliability index β	Maximum annual probability of failure
4	Particularly considerable consequences (atomic reactor).	4.26	10^{-5}
3	Considerable consequences (shopping centre)	3.71	10^{-4}
2	Moderate consequences (office building)	3.09	10^{-3}
1	Limited consequences (house)	2.32	10^{-2}

A thorough description of the historical development of design loads for wind actions and snow loads is presented by Meløysund et al. (2004).

SELECTION CRITERIA AND METHODOLOGY

Limits of use

The consequences of a collapse are greater in buildings in which many people are present than in buildings with few people. A collapse in public buildings such as sports halls, shops and the like has therefore greater consequences than, for example, in storage facilities in which it is less probable that people will be present. This is also apparent from the reliability approach set out in figures in Table 2 in which, under current rules, more stringent requirements are imposed on structures whose collapse may have major consequences.

Temporary structures are often more poorly planned and designed than permanent structures. This is in accordance with Norwegian codes if the building is designed to have a short lifetime and the return period for the environmental loads is adjusted for this. However, temporary structures often remain in use for a much longer time than expected. This means that the safety level for such structures in practice often is too low.

Material use and geometry

For light roofs, the specific weight is often low compared to the snow load that the roof is required to withstand. If the snow load exceeds the design value, the total load has increased virtually the same percentage as the snow load. If the specific weight had been high, the percentage increase would have been much smaller. Lightweight structures are therefore more vulnerable to an increase in snow load above the load for which the structure is designed than heavy structures. In other words, heavy structures have greater built-in safety when the snow load increases beyond the load that the structure is designed to withstand.

Another selection criterion is the maximum span of a building. The consequences of a collapse in buildings with large spans are usually great.

A number of types of construction may be sensitive to unbalanced loads. When the structures are being cleared of snow, this may in worst-case make the stresses in the structure larger than before the snow clearance started. There are many examples of snow clearing leading to the collapse of structures. It is therefore important to know whether the structure can carry the unbalanced load that arises during snow clearance.

Year of construction, loads and geographical location

Design loads on buildings have changed considerably in the period from 1949 till today. The year of construction may therefore tell something about the building's safety level. In general, older buildings in high-snowfall areas may have a lower safety with respect to snow loads than newer buildings. The difference in safety level with respect to wind action is probably somewhat less.

The safety level is probably affected mostly in areas that are heavily exposed to the environmental loads, when snow loads and wind actions in the regulations are increased from general loads that have applied to the entire country to differentiated loads that are adjusted to the actual environmental load variation in Norway. Increased wind actions therefore probably have the greatest consequences for coastal areas from northwest Norway northward. Locally, roughness of terrain and topography may be of great significance for the wind actions that the buildings experience. Inland areas high above sea level are most vulnerable to increased snow loads. Locally, topography and wind action is also important for the snow loads that the building experiences.

The construction process

Questions may be raised as to whether buildings erected by way of voluntary communal work or that are self-built, are more vulnerable to collapse than other buildings. It has been claimed that savings on design costs and technical expertise in the construction phase are often made for such buildings. Such savings can lead to little or no documentation of the structures being produced, and there may be a lack of people with the necessary technical competence to take overall responsibility for the execution of the work. This can lead to unfortunate improvisations on site that is assessed by the person implementing the project as “good enough”. It is therefore reasonable to believe that there is a greater probability of weak points that can result in the sudden collapse of such buildings.

Prefabricated structures are often imported. It has been claimed that the design calculations do not always meet the design rules set out in Norwegian codes and that many structures have been designed for relatively small snow loads compared to Norwegian requirements. Structures have been imported from countries such as Denmark that are designed for snow loads well below those required in Norway.

The history of buildings

Reconstruction or rebuilding may lead to significant changes in both design loads and load-bearing capacity. Columns and beams in outer walls (for example) may be centrally arranged during rebuilding, and thus assume greater loads. The need to strengthen structural elements, including foundations, may be extensive and is not always met. When walls are removed or new openings established, the stabilising elements of columns can change, or the anchoring may change, resulting in reduced load-bearing capacity.

Modifying the construction of roof structures may result in load change. For example, roofs that are changed from e.g. roofing membranes to tiles acquire an additional load of about 0.5 kN/m^2.

Additional insulation of roofs in older buildings may lead to reduced snow melting. Assuming the same precipitation pattern, this may result in larger quantities of snow remaining on the roof than before the additional insulation.

Changing the use of buildings, which may lead to greater consequences in the event of collapse, makes it necessary to reassess the capacity of the structures. In the case of a change of use from for example a storage building to a building for public use, the requirement concerning maximum annual probability of failure becomes more stringent, and there may be a need to strengthen the building.

Selection criteria

It would be desirable to identify a selection of buildings that could at large be characterised as communal halls, sports halls, buildings used by many people, lightweight structures, prefabricated buildings, buildings with large spans, buildings supplied as package solutions, buildings with modified applications, buildings erected via communal voluntary work, temporary structures and converted buildings. These are building types all of which are regarded as being especially exposed to increasing snow loads and wind actions.

The number of buildings investigated has for economical reasons been limited to 20. This number of buildings is too small to render possible valid statistical analyses of the reliability of the building stock in Norway as a whole, but importance has been attached to the sample being random and having a geographical spread. The results may in this way be assessed as a representative trend for the parts of Norway that have experienced significant changes in the rules governing snow loads and wind actions. It was therefore decided that the buildings should represent ten municipalities in six counties.

The municipalities have been chosen in such a way that half be in an area exposed to high wind actions and the other half in a high-snowfall area. The municipalities are Andøy, Bardu, Fræna, Grane, Kristiansund, Nittedal, Røyrvik, Tromsø, Trondheim and Ørland (see Fig. 3). Tromsø, Bardu, Grane, Røyrvik and Nittedal are situated in high-snowfall areas. Andøy, Ørland, Trondheim, Kristiansund and Fræna are in areas exposed to high wind actions.

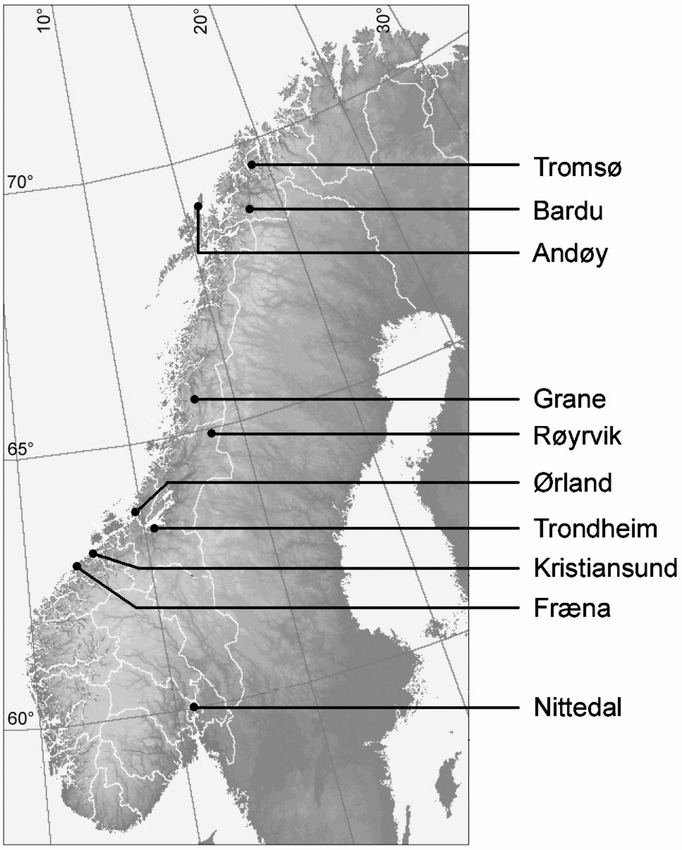

FIG. 3. Geographical localisation of the investigated buildings

In light of the fact that the regulations governing snow loads and wind actions have changed over three periods of time, it was decided that the sample should represent these periods. The periods can briefly be characterised as:

- Before 1970, when the 1949 building regulations were in force.
- Between 1970 and 1979, when NS 3052 was in force.
- After 1979, when NS 3479 was in force.

The buildings are all compared with today's design rules, including the current reliability code, NS 3490 (Standards Norway 1999), the current rules for determining snow loads, NS 3491-3 (Standards Norway 2001), and the current rules for determining wind actions, NS 3491-4 (Standards Norway 2002a).

To fulfil the requirement for randomness in the sample of buildings, the Norwegian Mapping Authority was asked for permission to search the GAB Register. However, the search criteria available proved to be limited. For buildings older than 1983, the data in the register is normally limited to details of the building's identity, the building type, ownership and possibly the address. For buildings erected after 1983, more information is available. A search based on selected building types reduced the sample from the approximately 3.7 million buildings in the register to around 9,000 buildings in the municipalities in question. In the search results, 10 to 12 buildings have been chosen from each of the 10 municipalities selected. In selecting the buildings, the time when the building was registered or erected was used as an indicator of the building's age. Where the buildings' floor space was stated, this has been used as an indicator for finding buildings comprising main load-bearing structures with spans of more than 10 metres.

The selected municipalities were then asked to provide the following information for each of the chosen buildings:

- A copy of the building licence application form.
- Copies of plan drawings and front elevations used in the building licence application.
- Confirmation on whether the municipality had archived construction drawings and design calculations or not.

The information has been used to select the buildings that will best suit the original priorities of the investigation. To make the investigation practicable, buildings for which documentation existed was given priority.

Selected buildings

Based on the assessments above, 20 buildings were selected (see Table 3, LAST PAGE). The table lists the municipality in which the buildings were selected, the building type and the requirement that currently applies to characteristic snow load on the ground and to the reference wind velocity. As shown in the table, attempts have been made to keep the selected buildings as anonymous as possible. Problems in obtaining the necessary documentation implied that an investigation of only one building was conducted in two of the municipalities, while this was extended to three buildings in two other municipalities.

Three of the buildings were constructed in the period before 1970, eight were built in the period 1970-79 and nine were built in the period after 1979. This implies that the loads are determined by the 1949 building regulations for three of the buildings, by NS 3052 for eight of the buildings and by NS 3479 for the latest nine buildings.

Project documentation investigation and field study

Calculation models, loads, forces and solutions used when the buildings were constructed have been investigated. The forces in the structure were then determined in accordance with new load requirements, and the capacities checked in accordance with new design rules. In the light of these analyses, the structure's utilization ratio has been determined in accordance with new calculation rules, and the need for reinforcement assessed.

On site, it has been investigated whether the structures have defects or deficiencies that are not apparent from the project documentation investigation. Special attention has been paid to the investigation of whether the construction is in accordance with the documentation, and whether there are weaknesses in the structure owing to reduced durability or due to reconstruction.

RESULTS

Geometry and material data

External dimensions, maximum spans and the material of the main load-bearing structures are shown in Table 3. The building's external dimensions are quoted as width, length, height and roof slope. The height indicates the cornice height for buildings with approximately flat roofs and the roof ridge height for buildings with other roof shapes. Additions or extensions that are not included in the assessments have not been included in the dimensions.

As is apparent from the values in the table, the buildings selected can be characterised as medium-sized buildings with medium spans. The roof slope varies between 0 and 26 degrees. All the buildings are of low height relative to their width and length. Essentially, the buildings included in the investigation are lightweight constructions, because buildings of this type are empirically expected to be most vulnerable.

Availability and scale of the documentation

When the investigations started, the authors were prepared for the fact that it might be difficult to obtain full documentation on the load-bearing structures in the buildings, which in this context have been defined as design calculations and structural drawings. Although there were requirements in the building regulations up to 1997 that design calculations should form part of the building licence application, it is well known that many municipalities have not enforced this requirement.

In the light of the information supplied by the municipalities, a total of 20 buildings were selected. Buildings with available documentation were given priority. It was decided at an early stage that built-in structures would not be opened and investigated. It was therefore necessary to obtain the best possible documentation so that built-in structures were known from the documentation. If there were a link between available documentation in the municipality and existing documentation, such a selection criteria would lead to the buildings most extensively planned being included in the investigation. Buildings that are planned in detail are probably also those with the fewest defects. It has not been possible to assess the significance of this aspect within the scope of this investigation.

A lack of important documentation for buildings included in the investigation can affect the results. The calculations must then be based on our own assumptions and assessments, which may be different from the constructor's (see Table 3 for information on available structural calculations). Deficient information on hidden, structural measures may then be significant. A lack of documentation makes it difficult to uncover the reason for chosen structural designs unambiguously.

All buildings in the investigation were approved for erection by the local authority (the municipality in which they are located). But, according to the available documentation, only 14 of the selected buildings proved to be designed by professionals. The actual number of buildings designed by professional is probably higher.

Changes in design snow loads and wind actions for selected buildings

Current requirements for characteristic snow loads on the ground and characteristic gust velocity pressures against the selected buildings are presented in Table 3. In the table, Andøy 2, Fræna 1 and Nittedal 1 are quoted with a) and b) versions. Here, a) means the original building and b) means additions (or extensions). Furthermore, the changes in design loads on the buildings are shown, where current requirements are compared with the requirements that applied when the building was being designed. Table 3 shows that the changes in design snow loads vary between 0.8 and 2.7 and have a mean value equal to 1.6. The changes in design wind action against the buildings vary accordingly between 0.4 and 1.4 and have a mean value equal to 0.9. In other words, the design snow load has on the average increased, while the design wind action has on the average been reduced.

As Table 3 indicates; only two buildings in two municipalities experience reduced design snow loads, one experiences an unaltered load level, while the rest experience increased snow loads. The changes in the rules for snow loads have therefore been of major importance to the requirement concerning design snow loads on most of the buildings that have been investigated. Buildings with a low roof slope dominate the investigation. Pitched roofs with roof slopes of between 15° and 60° have been given reduced shape factor for snow loads on the lee side of the roof. For the seven buildings with roof slopes > 15°, the increase in design load is on the average 1.4, which is somewhat lower than the mean value for all the buildings.

The changes in the wind action rules have not been as important as the change in the snow load rules for the design loads on the buildings investigated. As Table 3 shows, the changes in the rules have only resulted in a significant increase in the wind action on the buildings in the coastal municipalities of Andøy and Fræna. The buildings included in the investigation were low in height relative to their width and length. For buildings with this form, the sum of the shape factors against the windward and lee wall is equal to 0.85 in NS 3491-4, while the factor may become 1.5 for a high building. In earlier codes, the corresponding shape factor is 1.2, irrespective of the height of the building. In other words, the shape factor has become significantly lower for the building form that dominates the selected buildings, while it would not have dropped so low if the buildings had been high relative to their length and width. The reduction in design wind action for the selected buildings would therefore not apply for example to high-rise buildings.

Capacity exceedings compared with load increases

The highest utilization ratio found for important structural components for the buildings investigated are summarised in Table 3. As the table shows, 18 buildings have a utilization ratio of more than 1.0. This represents 90 % of the buildings that were investigated. Although the design requirements for 95 % of the buildings have increased since they were built, one would assume that they had built-in reserve capacities that meant that fewer buildings experienced a utilization ratio of more than 1.0.

The design rules for the most important materials in the structures have changed since the buildings investigated were planned. Essentially, the materials load-bearing properties can be utilised to a higher degree now than in the past. If the buildings had been constructed in accordance with the regulations when they were built, one would therefore have expected that fewer than 18 buildings would have exceeded their capacity under current rules. The table also shows that 11 buildings have a higher utilization ratio than a load increase. This indicates incorrect planning, incorrect construction or rebuilding.

It is important that all owners of buildings know what value of snow load the roof is designed for, and have routines for monitoring the snow load on the roof and clearing it when necessary. When roofs are being cleared of snow, this may in the worst-case make the stresses on the structure greater than before the snow clearance started. There are many examples of snow clearing leading to the collapse of structures. Instructions on this are contained in "Snow loads on existing roof constructions" (Lisø et al. 2000) and Report HO-1/2001 "Guidelines on snow loads on roofs" (National Office of Building Technology and Administration 2001).

DISCUSSION

As mentioned earlier the selected buildings in the investigation are building types regarded as being especially exposed to increasing snow loads and wind actions. The exposed building types amount to 5 % of the total bulk of buildings in Norway (11 % of total building floor area).

90 % of the buildings investigated have too low capacity when compared with current design rules. Thus, potentially 4.5 % of the total bulk of buildings in Norway may have too low capacity according to current regulations. The design snow loads have increased for 95 % of the investigated buildings indicating an increase in design snow loads for 4.7 % of the total bulk of buildings. 55 % of the investigated buildings have higher utilization ratio than load increase, which may indicate incorrect planning, incorrect construction or rebuilding. Thus, potentially 2.8 % of the total bulk of buildings in Norway have higher utilization ratio than load increase. However, the investigation constitutes only 20 buildings, and thus has obvious quantitative weaknesses. It must nevertheless be regarded as an important pointer on challenges concerning reliability.

The investigation indicates too low reliability for a considerable number of buildings according to current building regulations. It could also be of interest considering the future reliability of the building stock taking into account possible climate changes. In Norway the design life for buildings is 60 years in general and 100 years for monumental buildings.

Research establishments in several parts of the world are addressing the risks associated with future climate change and the resulting impacts. According to Karl and Trenberth (2003) modern climate change is now dominated by human influences large enough to exceed the bounds of natural variability, the main source of global climate change being human-induced changes in atmospheric composition. Regional changes in climate, particularly increases in temperature, have already affected several physical and biological systems in many parts of the world, for example shrinkage of glaciers, thawing of permafrost and lengthening of mid- to high-latitude growing seasons (McCarthy et al. 2001). Norway's climate is extremely varied. One of the main reasons for large local differences in temperatures, precipitation and wind speed over short distances are the rugged topography. The country's long coastline and steep topography make it particularly exposed to extreme events like coastal storms, avalanches and landslides. Regional scenarios for climate change over the next 50 years in Norway indicate an increased risk for extreme weather. Together with a warmer climate, especially during winter, an increased risk for intense precipitation over parts of coastal Norway and more frequent incidents of strong winds along the coast of the two northernmost counties and off the coast is estimated. These scenarios, emanating from the project "Regional climate development under global warming (RegClim)" (see www.met.no), are downscaled from a global climate model run by the Max Planck Institute for Meteorology in Hamburg. According to these scenarios the future reliability of buildings in exposed areas could decrease.

CONCLUSIONS

The principal objective has been to obtain reliable indicators as to whether existing buildings in Norway meet current regulatory requirements concerning safety against collapse as a result of snow loads and/or wind actions. Some clear indications of aspects that ought to be considered as a representative trend for the building types investigated have been found.

18 out of 20 buildings have a utilization ratio of more than 1.0 (90 % of the buildings investigated). The design requirements for 95 % of the buildings have increased since they were built. Nevertheless, one would assume that the buildings had built-in reserve capacities resulting in fewer buildings experiencing a utilization ratio of more than 1.0.

It is difficult to obtain structural drawings and design calculations for existing buildings. Such documentation is particularly important when buildings are to have alterations or reconstructions carried out. Public authorities should therefore establish a system ensuring that such documentation is made and maintained.

The new rules for determining wind loads that were introduced in 2002 have led to most of the buildings investigated having greater calculated reliability against collapse owing to wind load than the current regulations require for new buildings. For buildings in municipalities exposed to wind, for tall buildings or in places with special topographical conditions, safety may, on the other hand, decrease. The new rules for determining snow loads, introduced in 2001, have led to most of the buildings investigated having lower calculated reliability against collapse owing to snow loads than the regulations now requires.

A careless approach is often adapted to planning, or that this process is completely omitted, in the case of alteration and additional work. This may lead to significant design capacity excess. Thus, rebuilding, reconstruction and addition (extension) projects must also be adequately designed.

The investigation indicates too low reliability for a considerable number of buildings according to current building regulations, when evaluating the possible consequences of the conclusions in a national perspective. Potentially 4.5 % of the total bulk of buildings in Norway may have too low capacity according to current regulations. Design snow loads may have increased for 4.7 % of the total bulk of buildings.

Scenarios for future climate change indicate both increased winter precipitation and increased temperature, and will result in changes regarding snow loads on roofs in parts of the country. An increase in frequencies of strong winds in areas also exposed today is also estimated. According to these scenarios the future reliability of buildings in these areas could decrease.

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TABLE 3. Summary of findings

Building	Built (year)	Type of building	Material[1]	Width/Length/Height (m)	Roof slope (º)	Max. span (m)	Snow[2] (kN/m^2)	Wind[3] (m/s)	Wind [4] (kN/m^2)	Changes in design roof snow loads	Changes in design wind loads	Max. utilisation ratio	Structural calculations available?
Andøy 1	1989	Greenhouse	Alum.	12/26/6	26	12	0.7[5]/4.5	31	1.3	0.9	1.4	1.2	Yes
Andøy 2a	1979	Terminal building	Timb./steel	14/45/7	15	18	4.5	31	1.5	2.0	1.2	1.5	Yes
Andøy 2b	1991						4.5	31	1.5	1.3	1.1	4.0	No
Bardu 1	1994	Community centre	Timber	18/42/9	22	12	5.0	24	0.8	1.2	0.7	0.8	No
Bardu 2	1984	Shopping centre	Steel/concr.	21/-/8	<5	21	5.0	24	0.9	1.2	0.8	1.5	No
Fræna 1a	1977	Storage depot	Steel	42/40/9	3	20	3.5	30	1.4	1.6	1.2	2.8	No
Fræna 1b	1991						3.5	30	1.5	1.2	1.3	-	Yes
Fræna 2	1978	Sports hall	Timber/steel	30/50/9	4	20	3.5	30	1.5	1.8	1.2	3.2	Yes
Grane 1	1987	Storage depot	Timber	10/24/7	22	10	7.5	26	0.9	1.4	0.8	1.5	Yes
Kristiansund 1	1959	Sports hall (swimming pool)	Concrete	17/51/12	14	17	2.5	30	1.3	1.3[6]	0.6[6]	1.3	Yes
Nittedal 1a	1955	Bus terminal	Sipor./steel	28/51/5	Flat	8	4.5	22	0.6	2.4[6]	0.4[6]	2.3	No
Nittedal 1b	1982						4.5	22	0.6	1.5	0.6	1.4	No
Nittedal 2	1984	Sports hall	Steel	44/36/10	16	18	4.5	22	0.7	1.7	0.7	1.8	Yes
Nittedal 3	1961	Storage depot	Timber	13/85/8	7	7	4.5	22	0.7	2.4[6]	0.8[6]	3.7	No
Røyrvik 1	1975	Sports hall	Timber/steel	12/22/6	Flat	12	8.0	25	0.7	2.4	0.8	1.6	Yes
Røyrvik 2	1973	Community centre	Timber	13/34/7	15	8	8.0	25	0.8	1.7	0.8	3.7	No
Tromsø 1	1991	Post terminal	Steel/concr.	43/84/8	Flat	24	6.0	27	1.2	1.4	0.7	1.2	Yes
Tromsø 2	1979	Goods terminal	Steel	48/48/9	Flat	24	6.0	27	0.8	2.7	0.6	1.1	Yes
Trondheim 1	1978	Sports hall	Timber	24/44/9	22	24	3.5	26	0.9	1.8	0.8	5.0	Yes
Trondheim 2	1977	Shopping centre	Steel	30/61/8	Flat	22	3.5	26	0.9	1.6	1.1	1.7	Yes
Trondheim 3	1982	Storage depot	Timber	12/36/6	18	12	3.5	26	0.8	1.7	0.7	1.6	Yes
Ørland 1	1985	Shopping centre	Concrete	13/64/7	Flat	13	3.0	30	1.4	1.0	1.1	1.0	Yes
Ørland 2	1991	Garage	Timber	8/10/4	22	8	3.0	30	1.2	0.8	0.8	1.8	No
Mean value							4.6		1.0	1.6	0.9	2.0	

1) Material in main load-bearing structure, 2) Current characteristic snow load on the ground, 3) Current reference wind velocity, 4) Current requirements concerning characteristic wind loads against building (gust velocity pressure), 5) Load according to the greenhouse code NS-EN 13031-1 (Standards Norway 2002b) when account is taken of a 15-year return period and thermal coefficient,
6) Change in characteristic load on building

Part C
Methods for climate adapted design

IX. **Lisø**, K.R., Kvande, T., Hygen, H.O., Thue, J.V. and Harstveit, K. (2006) A frost decay index for porous, mineral building materials. *Building and Environment* (submitted).

X. **Lisø**, K.R., Hygen, H.O., Kvande, T. and Thue, J.V. (2006) Decay potential in wood structures using climate data. *Building Research & Information* (in press).

XI. Rydock, J.P., **Lisø**, K.R., Førland, E.J., Nore, K. and Thue, J.V. (2005) A driving rain exposure index for Norway. *Building and Environment* **40**(11), 1450-1458.

James P. Rydock, the main author of Paper XI, developed the methodology and performed the analysis of climate data. Kim Robert Lisø initiated the work and contributed in the development of the methodology and with material about building envelope performance. Eirik J. Førland suggested the approach and contributed in the development of the methodology. Kristine Nore contributed in the analysis of weather data. Jan Vincent Thue contributed with material about building envelope performance. All secondary authors contributed to the accomplishment of the paper by providing comments to successive rough drafts made by the main author.

XII. Meløysund, V., **Lisø**, K.R., Hygen, H.O., Høiseth, K.V. and Leira, B. (2006) Effects of wind exposure on roof snow loads. *Building and Environment* (accepted).

The work was initiated by Vivian Meløysund and Kim Robert Lisø. Meløysund and Lisø have been the main authors of Paper XII. Section 2 "Background" is written by Meløysund. Hans Olav Hygen performed the analysis of climate data. Karl Vincent Høiseth and Bernt Leira have contributed with their extensive experience within the field of structural engineering. All secondary authors have contributed to the accomplishment of the paper by providing comments to successive rough drafts.

A frost decay exposure index for porous, mineral building materials

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Abstract

The disintegrative process of freezing and thawing of porous, mineral materials represents a significant challenge in the design and construction of building enclosures. In this paper we present a simple method for assessing the relative potential of a climate to accelerate frost decay based on multi-year records of daily air temperatures and rainfall, with special emphasis on masonry. Distributions of 4-day rainfall prior to days with freezing events provide quantitative information on the geographically dependent frost decay risk in porous, mineral building materials in a given climate. Data from 168 weather stations in Norway are analysed, using weather data from the reference 30-year period 1961 - 1990.

Keywords: building defects, building enclosure performance, building materials, climate adaptation, climatic impact, decay, freezing, Norway.

1. Introduction

Norway's climate is extremely varied. From its southernmost point (Lindesnes) to its northernmost (North Cape) there is a span of 13 degrees of latitude, or the same as from Lindesnes to the Mediterranean Sea. Furthermore there are large variations in received solar energy during the year. The largest differences are found in Northern Norway, having midnight sun in the summer months and no sunshine at all during winter. The rugged topography of Norway is one of the main reasons for large local differences over short distances. Norway is often regarded as a cold and wet country. The country shares the same latitude as Alaska, Greenland and Siberia, but has a rather pleasant climate compared to these areas. Thanks to its westerly location, on the east side of a vast ocean, with a huge, warm and steady ocean current near its shores and a dominating southwesterly air flow from the Atlantic Ocean, Norway has a much friendlier climate than the latitude indicates. The highest annual temperatures can be found in the coastal areas of the southern and western part of Norway. Skudeneshavn (Rogaland County) on the southwest coast has an annual normal temperature of 7.7°C. In 1994, Lindesnes lighthouse (Vest-Agder County) recorded the highest annual temperature ever, with 9.4°C. When excluding uninhabited mountain areas, the coldest area throughout the year is the Finnmark Plateau. One of the stations there, Sihccajavri, has an annual normal temperature of -3.1°C. The coldest year ever was in 1893, when Kautokeino (Finnmark County) recorded an annual temperature of -5.1°C. Sihccajavri equalled this in 1985. In the mountains, large areas have an annual

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temperature of -4°C or less. See Fig. 1 for an illustration of the Norwegian climate according to the Köppen climate classification system.

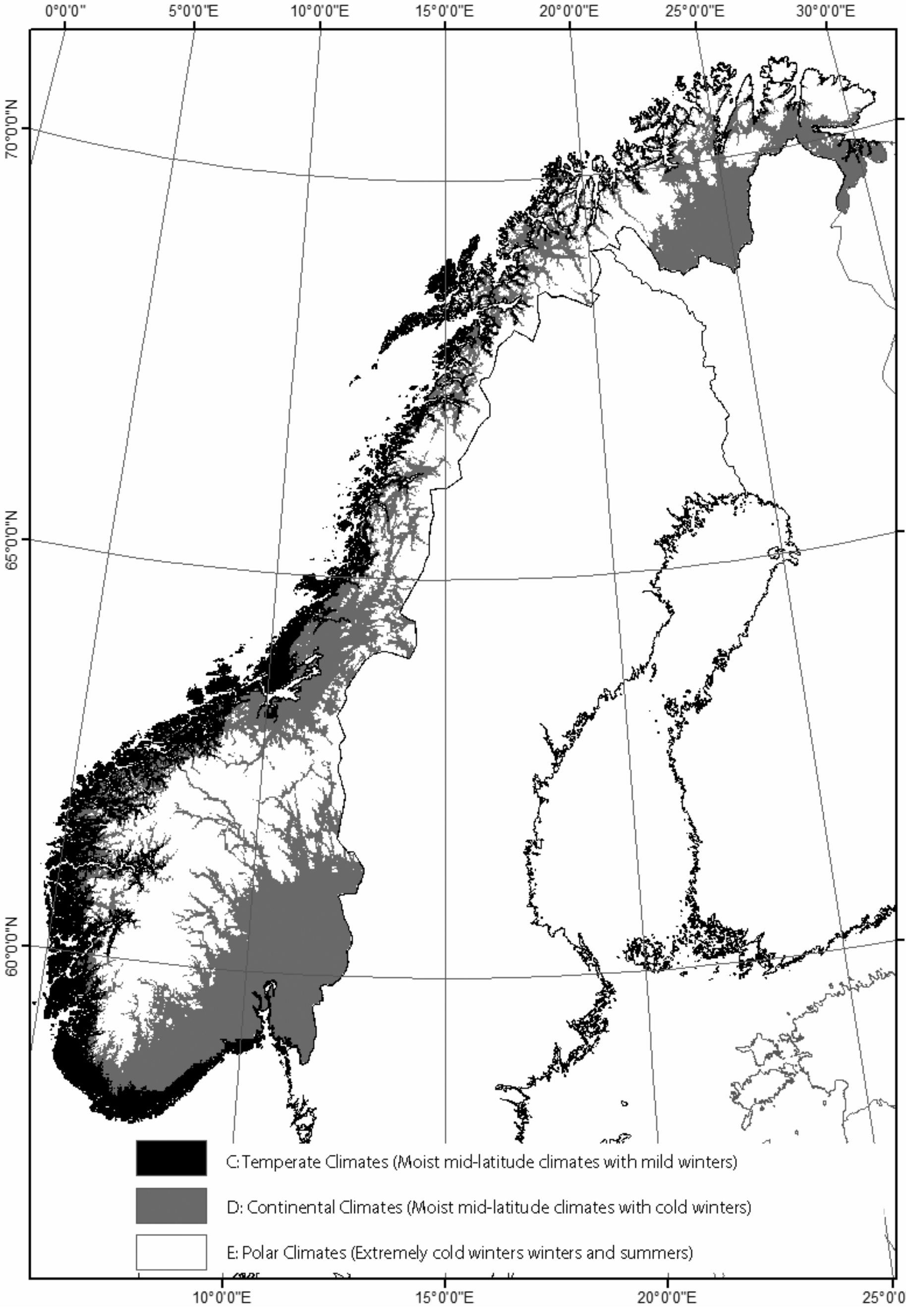

Fig. 1. The climate of Norway based on the Köppen climate classification system. The map is developed by the Norwegian Meteorological Institute (www.met.no), using weather data (annual and monthly averages of temperature and precipitation) from the reference 30-year period 1961–1990.

There are also large differences in the normal annual precipitation in Norway. The largest normal annual precipitation is found some miles from the coast of Western Norway. These amounts are also among the highest in Europe. Brekke in Sogn og Fjordane County has an annual normal precipitation of 3575 mm, and several other stations in this area follow close behind. Brekke has also the record for one-year precipitation, with 5596 mm in 1990. The inner part of Østlandet, the Finnmark Plateau, and some smaller areas near the Swedish border, are all lee areas in relation to the large weather systems mainly coming from the west. Common for these areas is the low annual precipitation and that showery precipitation during summer is the largest contributor. Øygarden at Skjåk (Oppland County, located less than 150 km in overhead line from Brekke) has the lowest annual normal precipitation with 278 mm. This is lower than the normal monthly precipitation for the 6 wettest months of Brekke. However, the lowest recorded precipitation for one year is only 118 mm, measured at Saltdal (Nordland County) in 1996.

The development of design tools for the assessment of frost decay risk is important because freezing and thawing of porous, mineral materials in combination with large amounts of precipitation represent a significant challenge in the design and construction of building enclosures in Norway. In this paper we present a simple climate exposure index for the assessment of geographically dependent frost decay risk based on multi-year records of air temperatures and rainfall in different parts of Norway. Ways of further development of the index are also discussed.

2. Background

The climate in Norway puts great demands on the design and geographical localization of buildings and the correct choice of materials and constructions. Since 1953 the Norwegian Building Research Institute (NBI) has undertaken analyses of building defects, both on behalf of the construction industry and in comprehensive field investigations. Results from an ongoing investigation of process induced building defects investigated in the 10-year period 1993-2002 (2378 building defect cases registered and described in 2045 assignment reports) reveals that defects related to the building enclosure constitute about two thirds of the cases. Moisture as the main source causing the defect replies for as much as 76% of all investigated cases in the 10-year period [1]. The lifetime, or decay rate, of building materials is of course strongly dependent on the local climatic conditions at the building site (i.e. temperature conditions and precipitation in the form of driving rain). Frost resistance may be a problem for porous, mineral materials, if exposed to repeated freezing and thawing when the moisture content exceeds certain critical values.

The development of design guidelines for buildings in severe climates through different climate index approaches has often proven a successful line of action in the pursuit of high-performance building enclosures. Scheffer [2] developed an index of the relative climate (using temperature and rainfall) to estimate the potential for decay of above ground wood structures. Cornick and Dalgliesh [3] have developed a moisture index for building enclosure design proposed for mapping North American climate regions according to moisture loading and the potential for drying. Djebbar et al. [4] introduces a freeze-thaw index as one of three hygrothermal indicators to characterise the moisture durability performance of masonry wall assemblies in high-rise buildings. Hoppestad's driving rain map for Norway [5], developed as early as 1955, is widely recognized. A new method for assessing driving rain exposure based on multi-year records of synoptic observations of present weather, wind speed and direction coupled with average annual rainfall totals has been developed by Rydock et al. [6].

In Norway, there are many weather-beaten areas where it is particularly important to take into account climatic challenges at the local level. The basis for calculating characteristic wind and snow loads on buildings is regulated by Norwegian and international standards. At present there are no corresponding, easily accessible design guidelines for the quantifying and sizing of e.g. moisture loads and frost damage risk. Furthermore, and even more disturbing, knowledge of sound building traditions and practice adapted to local climatic conditions seems to vanish in our quest for standardised cost-effective solutions. A navigable way of ensuring high-performance building enclosures is in our opinion to develop climate classifications or climate exposure indices for different building materials and building enclosures.

Today, frost resistance of brick, concrete and rendering mortar is tested according to methods given in different international and national standards. There are designated test methods for different countries. However, there exists no classification of climatic regions in Norway for frost durability assessment purposes, simply because there is no easily accessible data which can illustrate a correlation between the test exposure and the outdoor climatic exposure conditions. Determination of frost decay or frost damage risk ideally requires hourly values of air temperature and rainfall. Long-time weather data at most observing stations in Norway do not exist as hourly values.

According to NS-EN 771-1:2003 [7] “the freeze/thaw resistance of a clay masonry unit shall be declared by the manufacturer by reference to its applicability to masonry or elements subjected to passive, moderate, and severe exposure.” Annex B of the standard includes examples for masonry or masonry elements subjected to different climatic exposures dependent on the design of the construction, i.e. the risk of frost decay in a given climate. However, the climatic conditions are not specified in the standard. Until a European test method is available the freeze/thaw resistance of clay masonry units is to be evaluated and declared according to provisions valid at the intended place of use.

The European Committee for Standardization has arrived at an agreement on the development of a test procedure for the assessment of frost resistance of clay roofing tiles (NS-EN 539-2: 1998 [8]). The tiles shall, as stated in NS-EN 1304:2005 [9], be tested “according to the test method to choose with respect to the geographic zone designated for their use”. However, it is a paradox that the climatic exposure is to be based on geographical zones at a far too coarse national level, rather than regional- or local-level climate exposure data.

3. Moisture in materials

Every porous, mineral material exposed to moisture in vapour or liquid form will to some degree absorb moisture. Thus, there is always some amount of moisture in building materials. The moisture could have been added during production, or it could be attributable to contact with moist air in the surroundings, water from precipitation or from the ground. The content of moisture in a material depends on the type of material, the characteristics of the pore structure and the ways in which the moisture is bound in the material. The moisture content in a material at a certain point of time is normally also influenced by previous moisture impact (often referred to as the materials moisture history).

Table 1. Moisture transfer mechanisms and their driving forces.

State (or phase)	Transport mechanism	Driving force
Water vapour	(Water vapour) Diffusion	Differences in vapour pressure in air on each side of a material, structure or component.
Water vapour	Convection	Differences in air pressure on each side of a material, structure or component.
Liquid	Gravitation	E.g. leaks from roofs into underlying materials, structures or components.
Liquid	Wind pressure	Wind pressure can force liquid water in to cracks or other openings in the building enclosure.
Liquid	Capillary suction	Adhesion forces between water and the pore surface, allowing water being sucked into the pores. The surface stress of the water, the diameter of the pore and the angle of contact between the water and the pore surface determine the strength of this capillary force. At equilibrium the capillary force equals the pressure of the pore water multiplied with the cross-sectional area of the pore.

The main moisture transfer mechanisms in all types of building materials, structures and components are diffusion, convection, gravitation, wind pressure and capillary suction, or a combination of two or more of these mechanisms (see Table 1). The type and moisture state of the material determines which transport mechanism that will be dominant.

The moisture storing capacity and transfer properties of a material largely depends on the form, size and distribution of the pore system. The diameter of the pores can vary from several millimetres down to molecular dimension. There are not any straightforward ways of perfectly describing a porous material. The porous system could be interpreted based on the materials structure, as presented in Fig. 2. The maximal amount of water that can be retained in a material is determined by the porosity, defined as the volume of pores in relation to the total volume.

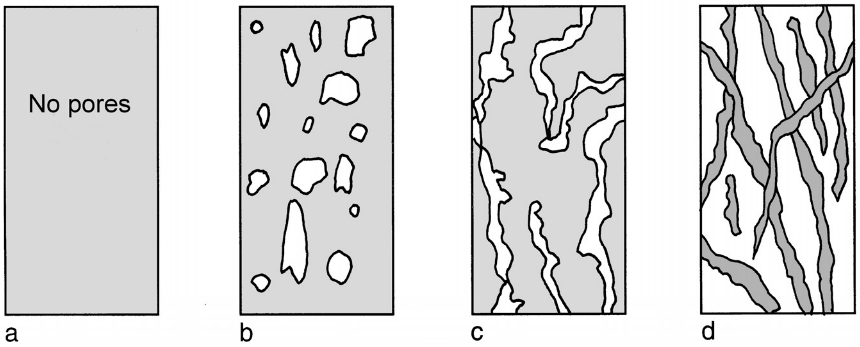

Fig. 2. Different types of material textures and pore systems: a) no pores (e.g. metal), b) continuous solid substance with locked pores (e.g. foam glass), c) both solid substance and pore system are continuous (e.g. concrete and wood), d) discontinuous solid substance (e.g. mineral wool and sand) [10].

4. Frost resistance

Frost resistance of porous, mineral materials is not a simple mechanical property. The frost resistance depends on a complex set of material properties and on the climatic impact on the material. Several researchers, e.g. Jacobsen [11] and Fagerlund [12], have thoroughly studied the effects of freezing and thawing on the durability of concrete. Freezing and thawing of masonry has not received the same kind of attention, in spite of the fact that frost damage on brick façades represents a considerable challenge in severe climates. Freezing of a façade is a gradual process, mainly governed by [13]:

- The rate of heat transfer through the façade.
- The increase in the concentration of dissolved salts in the still unfrozen pore water (the increase depresses the freezing point).
- The fact that the freezing point varies with the pore water pressure, i.e. size of the pore.

Exposure to saltwater may complicate the freezing process because the salt produces osmotic pressure and causes movement of water toward the top layer of the slab where freezing takes place [14]. Marchand et al. [15] presents a comprehensive review of the topic.

The frost resistance of a porous material largely depends on its mechanical properties, e.g. tensile strength, extensibility and creep. However, the determining factors to be considered are the degree of saturation and the properties of the pore system [13, 16]. Dührkop et al. [17] recommended the characterization of frost resistance of brick according to the degree of saturation. If the water content is higher than some critical degree of saturation, freezing will destroy the brick. The frost resistance of concrete is determined similarly.

As the temperature of a saturated porous material is lowered, the water freezes and expansion takes place. Freezing of water results in an increase in volume of approximately 9%. Damage occurs when the tensile forces in the pore system exceeds the tensile strength in the material. The extent of frost damage varies from surface scaling to complete disintegration as ice is formed. The disintegration starts at the exposed surface progressing through the material due to alternating freezing and thawing (see illustration in Fig. 3).

Fig. 3. A frost damaged brick wall (photo: NBI).

Repeated freezing and thawing causes progressive damage, as freezing causes migration of water to locations where it can freeze. The first freezing may introduce fine cracks where water may be located during the next freezing. This is how subsequent freezing and thawing gradually enlarge cracks until visible damage has occurred.

To ensure reliable frost resistance it is of crucial importance that the pore system of the material contains space available for expelled water close to capillary cavities in which ice is being formed. This is why air entrainment is added in concrete. However, the most reliable way of ensuring frost resistance of any porous material is to reduce the volume of capillary pores. A decrease in the volume of capillary pores also leads to an increase in tensile strength of the material, resulting in a material more resistant to ice expansion. Hence, frost resistant concrete should have a maximum water/cement ratio governed by the use of air entrainment as given in [18].

The degree of saturation of a façade material depends on the climatic conditions to which it is exposed, as well as the ability to absorb water. The suction rate is commonly used for classification of bricks. The masonry mortar composition depends to a high degree on the suction rate of the bricks, due to the fact that a suitable amount of water should be removed from the mortar to ensure optimal hardening conditions of the mortar itself and optimal extensibility and flexural strength of the masonry. (Both too much and too little suction may be unfavourable.) The suction rate may also serve as an indicator of the bricks frost resistance, by reflecting the volume of capillary pores and its ability to absorb water.

5. Methodology and results

The main purpose of the ongoing work has been to characterize the risk of frost decay or damage on a porous, mineral material exposed to a given climate, by combining knowledge on relevant material parameters and climate parameters. Or, in other words: To establish a quantitative connection between the number of freezing point crossings, the amount of precipitation in the form of rain and durability of different porous building materials. In the most general form a freezing and thawing exposure index (FTI) can be expressed as:

$$\text{FTI} = \text{Function of (climate properties, material properties)} \quad (1)$$

In this paper we will focus on the climate properties of such an index, using weather data from the reference 30-year period 1961-1990 (only weather stations with series of observational data of 10 years or more are used). The presented data are readily available for most observing stations in Norway. Data from thirteen observing stations in different parts of the country and with different climates are considered here as examples to illustrate the methodology (see Table 2, LAST PAGE). The selected locations are Kristiansand (observing station at Kjevik), Bergen, Stavanger, Lyngdal, Oslo, Røros, Ålesund, Ørland, Trondheim (observing station at Værnes), Bodø, Tromsø, Karasjok and Fruholmen (all shown on the map of Norway in Fig. 5), representing a wide range of climates.

Oslo, Lyngdal, Røros and Karasjok have a continental type of climate with relatively low annual precipitation, maximum precipitation in summer and a large annual temperature cycle. Karasjok and Røros have especially cold winters and low winter precipitation. Kristiansand, Stavanger, Bergen, Ålesund, Bodø, Tromsø and Fruholmen have maritime climate, high precipitation all over the year with a spring minimum, and a less distinct annual temperature cycle. The climate in Tromsø and Fruholmen is cooler and the cold periods during the winter dominate. The climate of Trondheim and Ørland is more or less in between continental and maritime, and cold winter periods are frequently broken by moist and warm air masses from the Norwegian Sea.

A potential high-risk frost decay area would have both a high number of freezing point crossings and large amounts of precipitation in the form of rain ahead of freezing events. An index should therefore express both of these elements of climate. The synoptic data used are daily air temperatures as measured three times a day (0600, 1200 and 1800 UTC), daily maximum and minimum air temperatures, and precipitation as measured 0600 UTC (covering the last 24 hours). To divide the precipitation amounts into snow and rain, the observed information of the present and past weather, noted three times a day, is used. All freezing events are considered, and air temperature transitions from values above 0°C to values below 0°C are counted to produce the index. Both measurements at the synoptic times (0600, 1200, and 1800 UTC) and daily maximum and minimum air temperatures are used to accomplish this. Precipitation in the form of rainfall for days where a freezing event has occurred and the prior 48 hours (2 days), 72 hours (3 days) and 96 hours (4 days) is counted. These monthly 2-day, 3-day and 4-day spells of rainfall are accumulated for one year.

Averaging the calculated annual climate indices over the 30-year reference period 1961-1990 resulted in a ranking of the relative potential of a climate to promote accelerated frost damage or frost decay for the thirteen stations, from highest to lowest, as presented in Table 2 and illustrated in Fig. 4. A high frost decay exposure index (FDEI) value indicates a high risk of frost decay or frost damage.

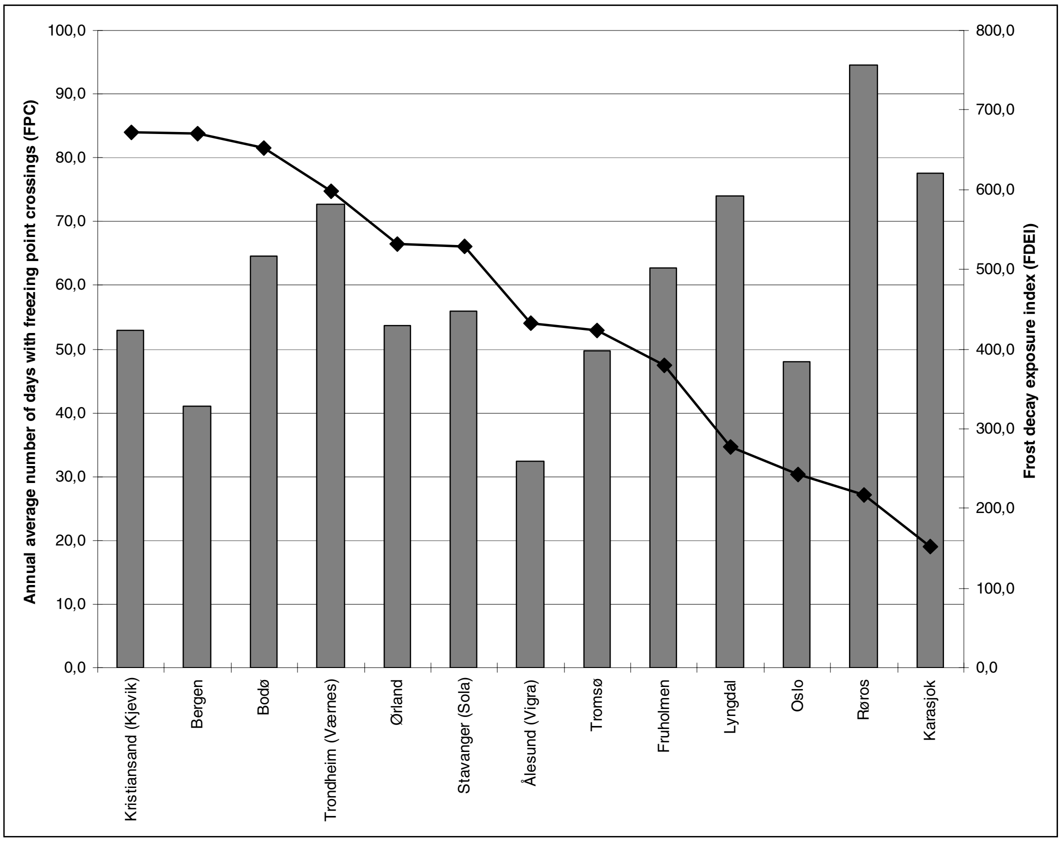

Fig. 4. Frost decay exposure index (FDEI) for the thirteen example stations, presented in a combination diagram. The annual average number of freezing events is given in columns, with values on the left side axis. Values for the resulting average year total frost decay exposure index (see line) are given on the right side axis. Weather data for the reference 30-year period 1961 – 1990 is used, summing 4-day rainfall prior to freezing events.

The results can be assessed qualitatively as follows: Kristiansand and Bodø, on top of the list for both 2-day, 3-day and 4-day sums of rainfall prior to freezing events, have large amounts of rainfall coupled with a sizable number of freezing events per year, and therefore represent the highest frost decay potential. Lastly, Røros and Karasjok have a high number of freezing events, but a very small average rainfall, especially in winter months. A few localisations are changing one place on the ranking dependent on the number of days of rainfall counted. Bergen is especially to be noted, as it climbs from number five when summing 2-day rainfall to number 2 on the ranking when summing 4-day rainfall, in particular due to extreme amounts of rain. Still, the bottom four localisations on the ranking are independent of the number of days of rainfall summed prior to days with freezing point crossings. This also applies for the top four localisations on the ranking, when Bergen is left out of account, indicating a robust method of characterising climates to promote frost decay. Damaging rain penetration in porous, mineral building materials requires a long-lasting absorption of moisture. Subsequent and repeated freezing events may destroy the material, or contribute to accelerated decay and thus reduced lifetime, if the water content is higher than the critical degree of saturation for the material at the time of freezing.

The frost decay exposure index (FDEI) is thus defined as the accumulated annual average sum of 4-day rainfall prior to days with freezing events. A 4-day spell of rainfall is shown to provide a reliable basis for climate differentiation of frost decay risk.

A national map of the calculated frost decay exposure indices is presented in Fig. 5, based on climate records for 168 weather stations in Norway and summing 4-day rainfall ahead of freezing events.

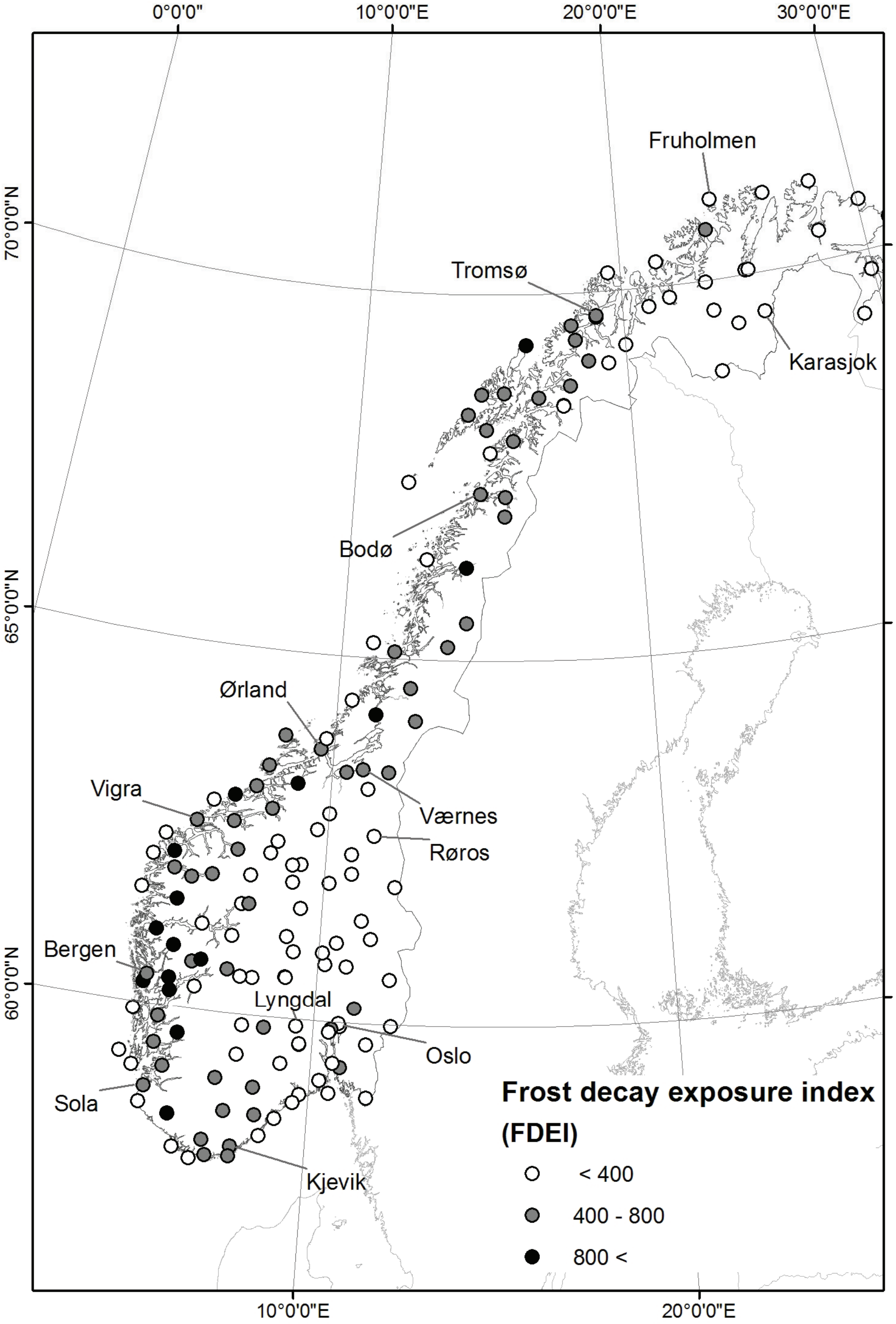

Fig. 5. Frost decay exposure index (FDEI) map for Norway: relative potential for a climate to accelerate frost decay or promote frost damage. Weather data for the reference 30-year period 1961 – 1990 is used, summing 4-day rainfall prior to freezing events.

A possible objection to the presented method could be that the index does not include the effects of wind. The moistening of e.g. a façade material is of course dependent on geographic orientation and wind conditions. But, in the end, the relative potential of a climate to promote frost decay or frost damage is basically guided by the two climate parameters included here, namely freezing events and rainfall.

6. The way forward

In Norway, about 100 stations cover the normal period, and have well enough observational programs to be used. Another 100 stations have long series that, though partly outside the normal period, can be coupled to the normal period. The next step may be to look at shorter series of a choice of stations that have a more frequent observational program. During the last 3-10 years, automatically recorded hourly values of temperature and precipitation at some 30-40 stations exist, but the quality of the hourly precipitation data has to be analysed. It is of interest to look at those data to find out whether improved climate indices may be compiled.

An important goal of future work is to further develop the index to provide quantitative information on the connection between climatic exposure in different regions and durability of different porous, mineral building materials (as indicated in this paper). This work will also include analyses of the influence of frost period lengths on the assessment of frost damage risk mapping.

Field investigations and laboratory testing of different materials are needed for validation and further improvement of the index. An important issue to be addressed is the connection between frost resistance and suction rate, especially of interest for clay bricks.

Research to address these issues are currently in progress as part of NBI's research & development programme "Climate 2000" [19], along with several other approaches in the pursuit of design tools using climate data and strategies for risk management of climate change impacts [20]. This is particularly important with respect to the preparation of additional Norwegian appendices to international standards associated with the various types of climatic impact. The "robustness" of the Norwegian building stock will also be addressed as part of the programme, including the development of methods for classifying different climatic parameters (based on historic weather data and scenarios for future climate development under global warming) and their impact on building enclosure performance. The index can be used as a tool for assessment of changes in decay rates due to climate change under global warming incorporating data from regional- and local-level climate change scenarios.

7. Conclusions

Frost resistance of brick, concrete and rendering mortar is tested according to internationally standardised methods. Test methods are given for different countries (dividing countries in far too coarse national-level climate zones), but there exists no classification of local- or regional level climate zones for frost durability assessment purposes. Frost decay assessment methods are also needed in the planning and design of high-performance building enclosures. A relative potential of frost decay or frost damage of mineral materials exposed to a given climate can be expressed using a simple index incorporating information about number of freezing events and 4-day rainfall sums prior to freezing events for the different months of the year, based on multi-year records of daily air temperatures and rainfall data. The principal advantages with the presented method are that the results are based on long-term series of climate data that are readily available. The method will be used as a foundation for the further development of a frost decay exposure index to characterize both climates and material properties for geographically dependent frost damage risk assessments. The proposed climate index is to be justified in the future in relation with building defects observations in different climates.

Acknowledgements

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Table 2. Weather data for the thirteen example stations (reference 30-year period 1961-1990). FPC = Annual average number of days with freezing point crossings (from plus to minus). FDEI = Frost decay exposure index, average year total (for 2-day, 3-day and 4-day sums of rainfall prior to days with freezing events). The calculated annual climate indices, averaged over the reference period, are presented in a ranking from highest to lowest index values.
Annual average precipitation totals (P, in mm/year) are provided for information.

Location	FPC	FDEI	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec	P (mm/year)
FDEI for accumulated 2-day sums of rainfall															
Kristiansand (Kjevik)	52,9	292,0	68,9	36,5	39,1	10,2	0,2	0,0	0,0	0,0	0,0	8,6	52,2	80,0	1299
Bodø	64,6	286,1	47,6	34,6	36,8	21,8	3,8	0,6	0,0	0,0	3,2	29,5	47,3	60,2	1020
Trondheim (Værnes)	72,6	283,2	40,0	32,0	44,4	24,6	3,9	0,0	0,0	0,0	1,7	20,9	44,1	71,7	892
Ørland	53,6	242,9	37,2	33,9	38,1	21,6	1,3	0,0	0,0	0,0	0,2	11,1	40,0	61,5	1048
Bergen	41,1	237,9	44,0	38,3	49,1	18,9	0,0	0,0	0,0	0,0	0,0	1,2	20,8	66,5	2250
Tromsø	49,8	231,9	32,9	25,6	22,0	23,0	5,8	0,7	0,0	0,0	6,2	44,2	40,8	33,5	1031
Stavanger (Sola)	55,9	210,0	41,0	31,0	29,7	15,5	2,2	0,0	0,0	0,0	0,0	7,0	35,1	48,7	1180
Fruholmen	62,8	200,5	33,5	24,8	17,9	18,8	9,1	1,1	0,0	0,0	1,3	19,4	42,2	35,2	830
Ålesund (Vigra)	32,3	197,9	32,9	25,2	29,3	20,2	0,0	0,0	0,0	0,0	0,0	2,1	26,6	59,6	1310
Lyngdal	74,0	124,3	9,6	6,6	16,4	13,3	1,6	0,0	0,0	0,0	6,9	31,9	31,2	8,1	797
Oslo	48,1	112,2	14,8	11,0	23,1	11,2	0,3	0,0	0,0	0,0	0,2	8,1	24,1	20,3	763
Røros	94,6	97,9	3,6	3,4	6,0	10,2	10,3	4,4	1,1	1,5	15,6	23,5	11,6	6,2	504
Karasjok	77,6	70,1	0,9	1,1	0,7	8,5	9,5	1,3	1,1	2,2	14,9	19,2	8,5	1,7	366
FDEI for accumulated 3-day sums of rainfall															
Kristiansand (Kjevik)	52,9	483,0	102,8	62,3	66,5	25,3	0,3	0,0	0,0	0,0	0,1	20,1	93,8	118,6	1299
Bodø	64,6	470,2	78,0	51,4	59,7	39,9	7,4	0,6	0,0	0,0	6,7	50,1	81,3	94,4	1020
Bergen	41,1	460,8	79,2	80,8	100,6	36,6	0,0	0,0	0,0	0,0	0,0	3,1	45,7	122,1	892
Trondheim (Værnes)	72,6	445,7	60,5	49,8	67,3	39,5	6,6	0,1	0,0	0,0	3,1	40,3	69,7	108,3	1048
Ørland	53,6	390,4	60,6	55,0	59,9	36,1	2,8	0,0	0,0	0,0	0,2	19,3	64,5	94,5	2250
Stavanger (Sola)	55,9	369,8	68,3	55,4	48,7	27,9	3,4	0,0	0,0	0,0	0,0	17,5	67,0	81,8	1031
Tromsø	49,8	329,1	43,8	37,3	32,3	35,1	8,7	0,8	0,0	0,0	8,7	67,1	60,8	46,0	1180
Ålesund (Vigra)	32,3	311,8	51,9	39,9	47,7	31,7	0,0	0,0	0,0	0,0	0,0	2,9	45,8	90,2	830
Fruholmen	62,8	289,6	46,6	34,0	27,9	27,5	13,6	1,5	0,0	0,0	1,9	30,7	60,9	49,9	1310
Lyngdal	74,0	199,8	15,0	10,3	24,2	23,7	2,8	0,0	0,0	0,0	13,4	55,7	50,5	10,7	797
Oslo	48,1	178,9	21,9	17,5	38,4	19,4	0,3	0,0	0,0	0,0	0,2	15,5	37,2	30,3	763
Røros	94,6	155,5	3,8	4,5	7,7	15,0	17,0	8,4	2,6	2,7	29,2	39,8	16,7	7,6	504
Karasjok	77,6	112,7	1,3	1,2	0,9	12,9	16,1	3,2	1,1	4,0	28,8	29,1	11,2	2,3	366
FDEI for accumulated 4-day sums of rainfall															
Kristiansand (Kjevik)	52,9	672,6	133,0	86,4	97,2	42,1	0,6	0,0	0,0	0,0	0,7	33,3	132,5	157,0	1299
Bergen	41,1	670,0	118,4	125,5	153,2	51,5	0,0	0,0	0,0	0,0	0,0	5,9	71,5	157,8	1020
Bodø	64,6	651,8	109,5	69,1	82,4	58,0	10,8	0,6	0,0	0,0	8,8	72,7	114,6	124,6	892
Trondheim (Værnes)	72,6	598,9	82,2	66,3	87,2	56,4	9,1	0,4	0,0	0,0	4,0	60,5	91,2	140,8	1048
Ørland	53,6	531,8	84,1	74,6	79,5	52,5	4,8	0,0	0,0	0,0	0,3	26,6	88,0	124,6	2250
Stavanger (Sola)	55,9	528,8	95,8	77,5	70,3	39,5	4,2	0,0	0,0	0,0	0,1	27,6	96,4	118,1	1031
Ålesund (Vigra)	32,3	432,8	74,0	55,9	66,7	42,6	0,0	0,0	0,0	0,0	0,0	3,8	62,4	124,9	1180
Tromsø	49,8	423,1	57,0	48,2	41,2	46,1	11,8	1,0	0,0	0,0	12,6	92,2	77,7	56,2	830
Fruholmen	62,8	380,3	59,5	42,9	37,3	36,7	18,1	2,2	0,0	0,0	2,3	43,9	79,9	63,4	1310
Lyngdal	74,0	276,7	17,4	13,2	34,4	33,6	3,8	0,0	0,0	0,0	20,5	80,2	74,2	12,8	797
Oslo	48,1	242,5	28,8	22,3	52,9	25,6	0,3	0,0	0,0	0,0	0,2	23,0	52,5	38,7	763
Røros	94,6	216,3	4,7	5,7	10,0	20,7	24,0	11,7	3,3	4,6	43,2	56,3	22,2	8,5	504
Karasjok	77,6	152,2	1,4	1,5	1,0	16,8	22,0	5,4	1,1	5,9	41,5	38,8	12,9	2,7	366

Decay potential in wood structures using climate data

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Abstract:

The relationship between building materials, structures and climate is complex, and there is an urgent need for more accurate methods to assess building performance. E.g. the lifetime of wooden claddings is strongly dependent on the local-level climatic impact. This paper presents a national map of the potential for decay in wood structures in Norway, based on Scheffer's climate index formula. Weather data from 115 observing stations for the reference 30-year period 1961 – 1990 is used. The climate index distribution allows for geographically differentiated guidelines on protective measures. Detailed scenarios for climate change for selected locations in Norway are used to provide an indication of the possible future development of decay rates. Climate indices allowing for quantitative assessment of building enclosure performance may be an important element in the development of adaptation measures to meet the future risks of climate change in different parts of the world. Established quantified relations between climatic impact and material behaviour or building performance, can be used as a tool for evaluation of the need for changes in functional requirements. The presented work represents an example of a first step towards such measures. Ways to further improve the reliability of the index are also suggested.

Keywords:

building enclosure performance, climate adaptation, climate change, climatic impact, decay risk, Norway, wooden structures, wood decaying fungi.

Introduction

Wood has for centuries been the dominant cladding material for dwellings and smaller buildings in Norway. The performance of a wooden cladding depends on the quality of the wood material, the surface coating, the construction details and the climatic impacts they are being exposed to. The design guidelines for the use of wood as cladding material in façade systems with separate wind and rain barriers have been unaltered for many years (Lisø *et al.*, 2003a). The principle of two-stage tightening (with an outer rain protection layer, a ventilated and drained space and an airtight layer) was thoroughly studied in Norway in the 1960's (Birkeland, 1963; Isaksen, 1966), the results still being applied. The principle is even today a highly relevant research topic in the pursuit of high-performance building enclosures (e.g. Nore *et al.*, 2005). One feasible way of ensuring further development of design guidelines for the use of wood as cladding material is to develop climate classifications or climate exposure indices based on long-term series of climate data, allowing for climate differentiated design and protective measures in a country with extremely varied and harsh climate conditions.

This paper presents a national map of the geographically dependent potential for decay in wood structures above ground in Norway, based on Scheffer's climate index formula (Scheffer, 1971). Weather data from 115 observing stations for the reference 30-year period 1961 – 1990 are used in the calculations. A temperature scenario for climate development under global warming for the selected locations is also provided, with estimated index values for the next 50 years.

Methodology and results

Scheffer (1971) developed a formula to "yield an index of the relative potential of a climate to promote decay of off-the ground wood structures" (p. 25), and presented a climate decay risk map of the United States. The formula has later been applied to Canada (Setliff, 1986), and is still a widely recognized reference work in the development of applicable climate indices within the field of building physics. The formula, allowing for quantitative measures of decay potential, was developed to estimate needs for protection of wood structures (preservative treatment in particular). The formula (Equation 1) consists of a temperature factor and a moisture factor, the two most significant climate elements (in addition to air) guiding decay rates in wood due to fungi attack:

$$\text{Climate index} = \frac{\sum_{Jan.}^{Dec.}(T_{mean}-2)(D-3)}{16.7} \qquad (1)$$

T_{mean} is the mean monthly temperature (ºC). D is defined as the mean number of days in the month with 0.254 mm (i.e. 0.01 inch) or more precipitation (rounded off to 0.3 mm for the practical purpose of selecting data from the electronic records of observed precipitation). The product is summed for the respective months, January to December. The sum of products was originally divided by 16.7 to make the index for the United States fall within the range of 0 to 100. The denominator would be about 10 for Norway, based on the values calculated for the 115 observing stations in this work. However, for the purpose of relative comparison no alterations have been made to the formula.

2ºC is in Scheffer's work considered to be the low temperature limit for growth of major decay fungi in wood, and thus the mean monthly temperature is reduced by two degrees. The relationship between growth rate (or rate of decay) and temperature is considered linear from 2ºC up to near the temperature maximum, assuming for simplification that the rate of decay by fungus as influenced by temperature is proportional to the number of degrees by which the temperature exceeds this low temperature limit. Scheffer uses an approximation of the relation of growth rate of the species *Lenzites Trabea* and *Polyporus Versicolor* to temperature (a brown-rot fungus and a white-rot fungus respectively). The simplified linear relationship may not be valid for all types of wood decaying fungi and not for temperatures above 30ºC, but this is not decisive as there are no areas in Norway with mean monthly temperatures above 17,3ºC (maximum registered monthly temperature for the reference 30-year period 1961-1990, location: Studenterlunden, Oslo).

Wood decaying fungi will only be active if there is water present in the material. Growth of most wood rotting fungi requires moisture content in the material exceeding 20%. The low temperature limit for growth of wood decay fungi varies from type to type. Some develop at several degrees below the freezing point, others at more than 60 °C. All types of wood decaying fungi are heat sensitive and will die at high temperatures, and normally they survive at low temperatures. Most wood rot and mildew fungi in buildings in Norway is found to be growing at temperatures between 5 and 30°C (Norwegian Building Research Institute and Mycoteam as, 1997; Sedlbauer, 2001).

The moisture factor of the index is chosen based on the fact that duration or distribution of precipitation (and thus wetting) is generally more important than total precipitation in determining the moisture content of wood above ground. The chosen precipitation measurement is supported by field experiments (Scheffer, 1963). The moisture factor, the mean number of days in the month with 0.254 mm or more precipitation, was found to yield indices most proportional to actual rates of decay in experimental units in three different exposure sites in the US with significantly different climates. Relative decay potentials were estimated from rates of decay in untreated units of decay-susceptible wood species. The days of precipitation were randomly reduced by 3 to keep the index for the driest regions of the US near zero.

Climate indices are calculated according to Equation 1 for 115 weather stations in Norway, all having at least 10 years of high quality observations in the 30-year period 1961-1990. These calculations were based on mean monthly air temperatures (T_{mean}) and number of days with more than 0.3 mm precipitation (D), both being registered on a regular basis by the Norwegian Meteorological Institute. T_{mean} are calculated using a daily average (N) of air temperatures registered at 0600, 1200 and 1800 UTC and monthly minimum temperatures (T_{min}), as given in Equation 2:

$$T_{mean} = N - k(N - T_{\min}) \text{ where } N = \frac{T_{0600} + T_{1200} + T_{1800}}{3} \tag{2}$$

k is a local value to compensate for lack of hourly observations of air temperatures.

The calculated climate indices were used in a spline interpolation to create a smooth coverage of the index when producing the national decay risk map presented in Figure 1. This interpolation is fairly coarse with no adjustments for topographic effects, except what is captured in the observations at each weather station. Three index levels are outlined on the map (with boundaries delimited according to Scheffer):

- Low Decay Risk (less than 35, the least favourable conditions for decay),
- Medium Decay Risk (35-65)
- High Decay Risk (values greater than 65, favourable conditions for decay).

Index values, both monthly products and the year total, for a selection of weather stations are provided in Table 1 (all shown on the climate index map for Norway given in Figure 1).

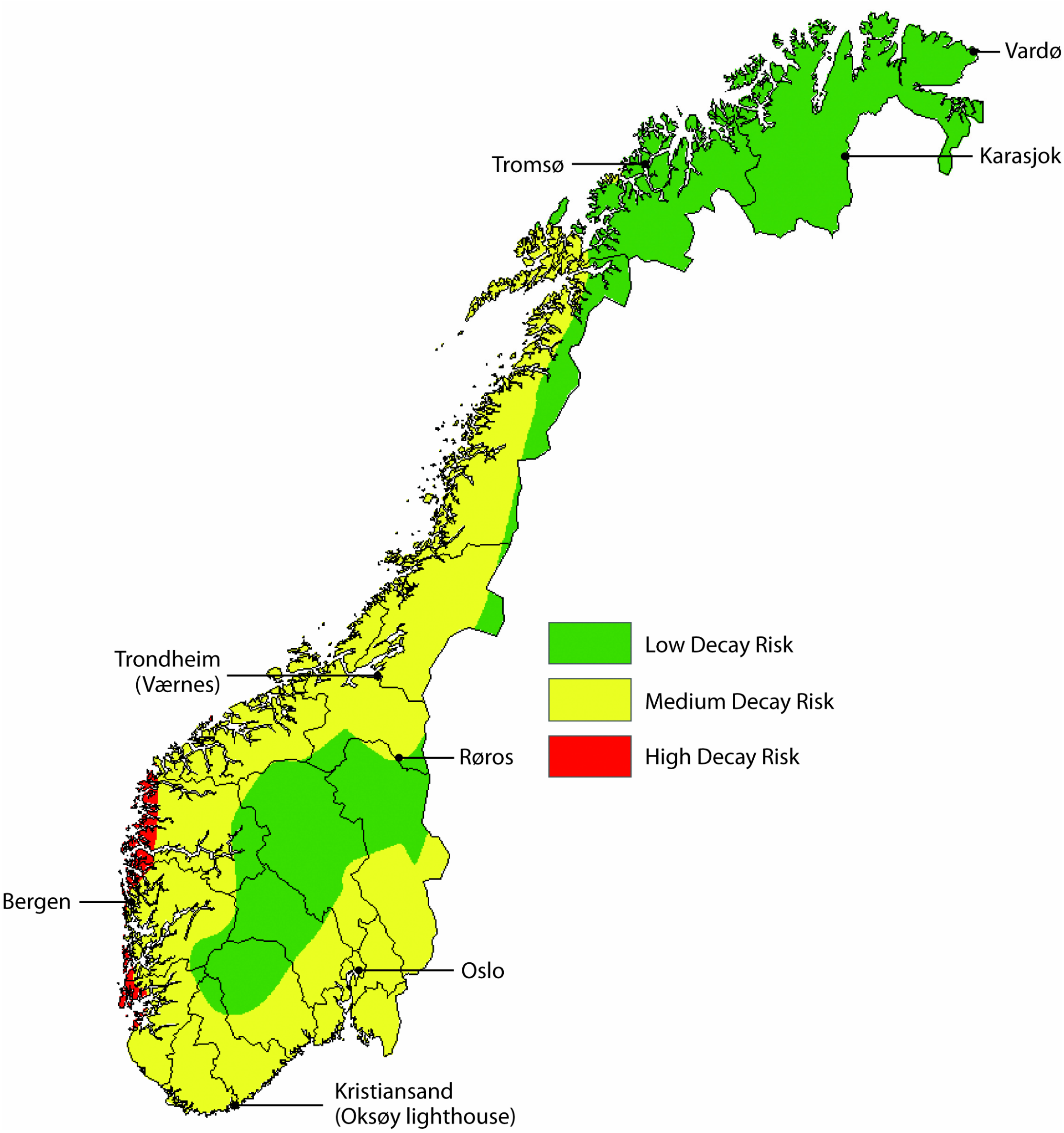

Figure 1 Climate index map for Norway: relative potential for decay in Norwegian wood structures based on Scheffer's climate index formula. Weather data for the reference 30-year period 1961–1990 is used.

The highest annual temperatures in Norway can be found in the coastal areas of the southern and western part of the country. When excluding uninhabited mountain areas, the coldest area throughout the year is the Finnmark Plateau. The largest normal annual precipitation is found some miles from the coast of Western Norway. The inner part of Østlandet, the Finnmark Plateau, and some smaller areas near the Swedish border, are all lee areas in relation to the large weather systems mainly coming from the west. Common for these areas is the low annual precipitation and that showery precipitation during summer is the largest contributor. As can be seen from Figure 1, the two northernmost counties (Tromsø and Finnmark), some areas in Nordland County near the Swedish border and the mountainous areas in southern Norway have the least favourable conditions for decay. Medium decay risk is found in the remaining and most densely populated parts of the country, except for the exposed coastal areas of the western part of the country where climate conditions most likely to promote decay prevails. Two of the largest cities in the country, Stavanger and Bergen, are situated in this high-risk area.

Table 1 Decay risk index values for eight selected locations (monthly values and year total) for the reference 30-year period 1961-1990, and a scenario index value (year total) for the period 2021-2050.

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Index 61-90	T_{change} (°C/decade)	Index 21-50
Vardø	0	0	0	0	1	3	5	6	4	1	0	0	20	0.22	27
Karasjok	0	0	0	0	1	6	9	7	3	0	0	0	26	0.46	37
Tromsø	0	0	0	0	2	6	10	8	5	1	0	0	33	0.28	43
Trondheim (Værnes)	0	0	0	2	5	9	12	11	9	4	0	0	52	0.29	66
Røros	0	0	0	0	2	6	8	73	4	0	0	0	28	0.28	36
Bergen	1	0	1	3	7	9	11	12	11	8	4	1	70	0.20	84
Oslo	0	0	0	1	6	9	11	10	7	4	0	0	48	0.25	57
Kristiansand (Oksøy lighthouse)	1	0	1	2	5	6	8	9	9	7	3	1	50	0.21	60

A temperature scenario (T_{change}) for climate development under global warming for the selected locations is also provided in Table 1 (derived from Benestad, 2005). The scenario values are based upon the estimated differences in monthly mean temperature between the periods 1961-1990 and 2021-2050, and are given as changes per decade. The most realistic scenarios for changes in global climate are based on coupled atmosphere/ocean/sea-ice General Circulation Models (AOGCM's) providing a comprehensive representation of the climate system (McCarthy *et al.*, 2001). The spatial resolution in these models is too coarse to reproduce the climate on regional or local scale, not allowing for complex physiography to be considered (e.g. high mountains, deep valleys and fjords). To deduce detailed scenarios for future climate development in different parts of Norway, both dynamic and empirical downscaling techniques are applied on global climate models (GCM) and regional climate models (RCM). Benestad (2005) uses an empirical-statistical analysis for monthly mean temperature for a multi-model ensemble of the most recent climate scenarios (Special Report Emission Scenario A1b) produced for the forthcoming Intergovernmental Panel on Climate Change (IPCC) Assessment Report 4 (AR4). The empirical-statistical downscaling incorporates local information for the locations, and additional geographical information is utilized in the spatial interpolation of the results.

Roughly estimated index values for the next 50 years are provided in Table 1 (for the 30-year reference period 2021-2050). The estimated decadal temperature change from Benestad (2005) is used to adjust the calculated historical values. The precipitation rates are kept unaltered in the calculations, but the scenario index values clearly points towards a pronounced increase in the potential for decay in wood structures at all locations. In general, climate change scenarios also indicate an increase in the average annual precipitation in Norway during the next 50 years, and thus strengthening this trend. The projected precipitation increase rates are generally smallest in southeastern Norway, and largest along the northwestern and western coast.

Concluding remarks and further work

Untreated wood cladding that is properly ventilated and drained has a relatively long lifetime even in harsh climates. A high-performance cladding is to a large degree ensured if the principle of two-stage tightening is applied. Still, the lifetime of the cladding is strongly dependent on the climatic impact on site. Preservative measures, both surface treatment and impregnation, is used to enhance the lifetime of the material. The presented national map of climate index distributions allows for geographically differentiated guidelines on protective measures in the form of impregnation, surface treatment or precautions in design of wooden structures. The map will be used as an important instrument in the continuous development of Norwegian technical guidelines for wooden building enclosures (e.g. the SINTEF Building Research Design Sheets, see Lisø *et al.*, 2005), allowing for climate differentiation in both protective design and preservative treatment of wood.

Extended use of climate-differentiated preservation can contribute to a reduction of the economic and environmental costs associated with preservative measures. The opportunities for both prolonged maintenance intervals and extended use of environmentally friendly wood preservatives in different climates should be subject to further investigations.

The quantitative connection between wood decay rates and climatic impact should also be further investigated. The moisture transfer mechanisms of wood are highly influenced by the surrounding climatic conditions. Field- and laboratory investigations are needed to further improve the reliability of the index for Norwegian climatic conditions, including measurements of decay rates in different climates and in different types of wood. Important issues to be considered are the low temperature limit for growth in wood decaying fungi in evidence in Norway, and appurtenant observed growth rates to temperature.

The built environment is experiencing extensive degradation and damage every year due to climatic impact. Projected changes in climatic conditions will further enhance vulnerability within the construction industry and the built environment (Lisø *et al.*, 2003b; Lisø, 2005). Climate change can increase the risk of decay of wood structures. Climate indices allowing for quantitative assessment of building enclosure performance or decay potential may be an important element in the development of adaptation measures to meet the future risks of climate change in different parts of the world. This and other indices, with established quantified relations between climatic impact and material behaviour or building performance, can be used as a tool for evaluation of changes in functional requirements or decay rates due to climate change under global warming incorporating data from regional- and local-level climate change scenarios as indicated in this paper. The presented work represents a first step towards establishing such measures. Thorough analyses of projected future climate index values, including assessment of uncertainty ranges, will be published in due course.

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A driving rain exposure index for Norway

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Abstract

Determination of driving rain exposure typically requires hourly values of rainfall and mean directional wind speed. Weather data at most observing stations in Norway are not recorded as hourly values and are therefore not amenable to this type of analysis. We present an alternative method for assessing driving rain exposures based on multi-year records of synoptic observations of present weather, wind speed and direction. Distributions of numbers of rain observations and wind speeds versus wind direction combined with average annual rainfall totals yield quantitative information about driving rain exposures at stations. Results from four weather stations in Norway are presented and discussed, using weather data from the period 1974–2003.

Keywords: Driving rain; Ventilated cladding; Building enclosure performance; Building stock; Weather observations; Norway

1. Introduction

Norway, by virtue of its location, is highly exposed to mid-latitude cyclones impacting Europe from the Atlantic Ocean. The topography of Norway is extremely varied, with a high percentage of mountainous terrain, many deep and narrow river valleys and fjords and a very long coastline extending from the Arctic Ocean in the north to the Norwegian Sea and open Atlantic Ocean to the west, to the North Sea to the south and finally to the relatively protected Skagerrak to the southeast. Not surprisingly, the nature and quantity of driving rain varies significantly across the country. There is, however, no practical tool currently available for assessing driving rain exposures in the planning and design of the built environment, and there has been little progress made during the past 50 years in the quantification and presentation of driving rain values at weather stations around the country. This is important because driving rain represents one of the greatest challenges in the design and construction of outer wall structures in Norway. In this paper, we present a new method for assessing driving rain exposures based on multi-year records of synoptic observations of present weather, wind speed and direction coupled with average annual rainfall totals.

2. Background

Direct measurement of driving rain (combined rain and wind, e.g. a measure of the amount of water passing through a vertical plane) would of course be the most natural means of quantifying driving rain loads at different locations. The equipment necessary to do this

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(a driving rain gauge), however, is not standard equipment for weather stations in Norway and consequently, driving rain is not routinely measured. Work on driving rain mapping, therefore, proceeded early on to investigating means of indirectly determining driving rain loads using ordinary wind and rain data. An overview of available Norwegian weather data and existing driving rain calculation methods are presented by Jelle and Lisø [1]. A driving rain map for Norway was developed as early as 1955 by Hoppestad [2]. The map separated average amounts of free wind-driven rain into four principal wind direction components (north, south, east and west). To acquire background data for the mapping, driving rain measurements (using driving rain gauges specially set up for this purpose) were made at four stations, every 12 h over a period of 3 years. For the same 3-year period, wind direction and velocity were recorded every 2 h at the same stations. The product of the wind component in each direction and the measured rain total (on a horizontal surface) was calculated for the period including the hour before and the hour after each wind observation during precipitation. These values were then summed for the 12-h periods corresponding to the driving rain measurements and a correlation coefficient between measured directional driving rain (from the north, south, east and west) and the product of directional wind and rain was determined. The coefficient was then applied to observational data from 1946 to 1950 where precipitation was measured twice daily and synoptic observations made three times daily to compute directional driving rain (in mm/yr) at each of these stations.

In order to accomplish this it was necessary to assume that precipitation events were uniform and started one-half of an observation interval before the first present-weather observation of rain and ended one-half of an interval after the last present-weather observation of rain in a continuous series of present-weather rain observations. A principal weakness in the practical application of this impressive work is that the directional dependence, with only four components, is not detailed enough to be much use in examining local topographical effects, which can be quite substantial over very short distances in Norway. Since the publication of Hoppestad's report, however, a period of almost 50 years, no further improvements have occurred in the area of driving rain mapping on a national level in Norway.

Currently, ISO 15927-3 [3] is available as a European pre-standard and provides two separate methods for calculating a driving rain wall index from wind and rain data. As defined in this document, a driving rain wall index is a measure of the quantity of wind driven rain impacting a point on a vertical wall. The first method detailed in the pre-standard, based on experience in Great Britain, requires hourly average wind speed and direction, as well as hourly rainfall amounts, for a period of at least 10 years (and preferably 20 or 30). Weather observations in Norway have not historically been recorded as hourly averages, and even today this is done at only a handful of stations at the largest airports in the country (though automated weather stations recording hourly wind and precipitation amounts are becoming increasingly common). A nationwide implementation of this method, therefore, is not practical at present.

The second method, which appears to be largely based on experience in France, does not require hourly wind and rainfall data. In this method, an index is introduced which is based on classification of the average weather conditions at a location for 12-h periods (or half-days), as moistening, drying or neutral. A moistening half-day is defined as a half-day with more than 4 mm of precipitation on a horizontal surface, with an average wind speed of greater than 2 m/s, with an average wind direction during the half-day within 60° of the perpendicular to the wall in question, and with the present weather code signifying some precipitation for at least three of the five observations during that half-day (The method assumes observations occur every three hours, so a 12-h period would include five observations, at 0, 3, 6, 9, and 12 h). A drying half-day, on the other hand, is a half-day with an average relative humidity less than 70%, with an average wind speed greater than 2 m/s, and with an average wind direction within 60° of the perpendicular to the wall direction in question. A neutral half-day is any half-day with conditions falling outside of the moistening and drying classifications. In this method, moistening days are given a value of $+1$, drying half-days -1 and neutral half-days 0. A cumulative sum is developed over a year, and an index is defined as the length in half-days of the longest moistening period (or 'spell', as used in the standard) in the year. At the time of writing of this paper, the definition of this index in the pre-standard is somewhat unclear.

Though observations at Norwegian weather stations are typically done only a maximum of three times during any half-day, there is nothing else about the nature of the meteorological observations in Norway that would necessarily preclude use of this second method detailed in ISO 15927-3. Twelve hour precipitation totals are available from most stations and average wind speed, wind direction and relative humidity for half-days could probably be reasonably approximated from the 3-a-day or 4-a-day synoptic observations that are the norm at weather stations in the country (see Section 3). The problem in this context is that the moistening/drying concept upon which the developed index is based is meant to be relevant for moisture transfer from the wetted exterior surface by capillarity into masonry-clad constructions. Masonry construction is deeply rooted in the Norwegian building practice. However, wood is the most common cladding material for dwellings and smaller buildings, and a great percentage of the building stock is built with wooden exterior cladding separated from the interior construction by a ventilated and drained air gap (two-stage tightening). A two-stage watertight façade is a design consisting of an outer rain protection layer, a ventilated and drained space and an airtight inner layer. The outer rain protection layer, i.e. the cladding, can be different kinds of wood panelling, metal sheeting or board claddings. In houses with ventilated wooden cladding, moisture migration by capillarity is certainly not the major form of moisture ingress into the inner construction from driving rain. Therefore, an index that yields information about the relative occurrence of weather conditions relevant for capillary moisture transfer into a masonry wall is not appropriate for determining the risk from driving rain of moisture uptake in an inner wall construction behind the air gap in a building with ventilated cladding. A different type of approach is needed.

Rather, by using a multi-year sample interval, enough observations of wind-plus-rain are accrued to obtain a representative picture of the relative frequency of driving rain from different directions at a weather observing station. Normalizing the frequency distribution by the annual rainfall amount at a station then allows for quantitative comparison of directional driving rain between stations. A wall index can then be calculated using the usual method of summing directional driving rain contributions from directions with wind blowing against a wall having a specific orientation [3,4].

3. Methodology and discussion

Synoptic observations from most weather stations in Norway include the 10-min average wind speed and direction at the time of observation as well as a numerical code (standardized internationally by the World Meteorological Organization [5]) identifying the state of the weather at the time of the observation. Observations are done four times daily (1, 7 AM, 1 and 7 PM local time) at the larger stations and three times daily (7 AM, 1 PM and 7 PM local time) at the more rural stations. Electronic records of synoptic observations go back to at least 1960 for most stations. As the present-weather codes are numerical, records of observations from many years are easily analysed in spreadsheet programs. There are six separate codes for rain and three for rain showers, listed in Table 1 below. Clearly there is an element of subjectivity and thus uncertainty in analysing codes representing the observer-determined type of rain that was occurring at a particular time and location.

Table 1
Codes for rain or rain showers used to select rain events in the synoptic observation data

Code	Synoptic weather description
60	Rain, not freezing, intermittent, slight at time of observation
61	Rain, not freezing, continuous, slight at time of observation
62	Rain, not freezing, intermittent, moderate at time of observation
63	Rain, not freezing, continuous, moderate at time of observation
64	Rain, not freezing, intermittent, heavy at time of observation
65	Rain, not freezing, continuous, heavy at time of observation
80	Rain shower(s), slight
81	Rain shower(s), moderate or heavy
82	Rain shower(s), violent

The strategy employed here was quite simple. We began by selecting all observations in the analysis period that coded for some type of rain (codes 60–65 or 80–82), the thought being that while the determination of whether a rainfall event was light, moderate or heavy, continuous or intermittent or showery was subjective, the appearance of one of these codes could confidently be construed as objective evidence that a rainfall event was associated with that observation time. Next, the selected observations were grouped according to the wind direction (in 10° increments) observed at the time of the rainfall event. The analysis period chosen was January 1, 1974 to December 31, 2003, the 30-year period representing the most recent climate in Norway.

Data from four observing stations in different parts of the country and with different climates are considered here as examples to illustrate the methodology. The stations are located in the cities of Oslo, Bergen and Tromsø, and at the airport serving Trondheim (about 30 km east of Trondheim). These four cities are shown on the map of Norway in Fig. 1. Average precipitation and wind speeds for the four cities are shown in Table 2. Oslo has a relatively protected location on the Oslo Fjord, and the wind speeds are generally low (average annual wind speed 2.7 m/s). Bergen, Trondheim and Tromsø are more exposed to mid-latitude cyclones coming in off the Atlantic Ocean, and have average annual wind speeds between 3.5 and 4 m/s. Bergen has by far the largest annual precipitation, with 2250 mm/yr. From this table alone one would be able to conclude that Bergen has by far the largest driving rain, Oslo the least, and Trondheim and Tromsø somewhere in between.

Table 3 lists the total average annual number of rain events for each station as well as the percentage of moderate/heavy observations for the 30-year analysis period. Not surprisingly, Bergen, with the highest average annual precipitation, had the highest number of annual rain observations with wind (245 out of a total of $365 \times 4 = 1460$ possible per year, or about 17%) and the highest average number of moderate or heavy

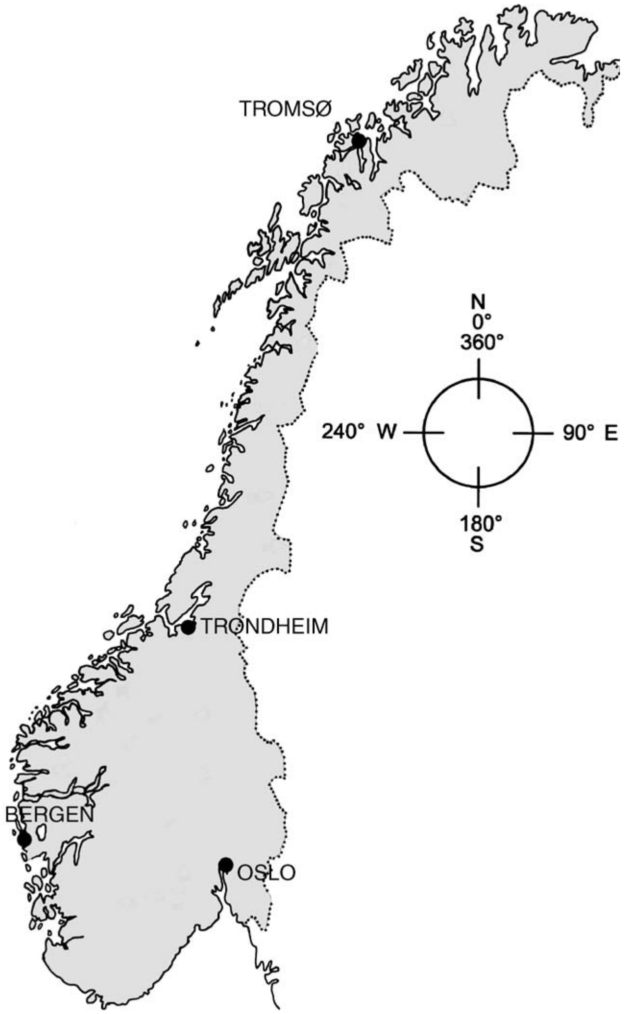

Fig. 1. Map of Norway showing the locations of the four weather stations used in this study.

Table 2
Average annual precipitation and wind speed for Oslo, Bergen, Trondheim and Tromsø, Norway for normal period 1961–1990

Location	Average annual precipitation (mm/yr)	Average wind speed (m/s)
Oslo	763	2.7
Bergen	2250	3.5
Trondheim	892	3.9
Tromsø	1031	4.0

Table 3
Average annual observations coded as rain (codes 60–65 and 80–82) and percentage coded as moderate or heavy rain (codes 62–65 and 81–82) from 1974–2003 at Oslo, Bergen, Trondheim and Tromsø, Norway

Location	Synoptic observations coded as rain (per year)	Moderate/heavy as a percentage of total (%)
Oslo	98	23
Bergen	255	18
Trondheim	167	10
Tromsø	133	15

events. Oslo had the lowest number of annual rain observations (less than half the number observed in Bergen) but the highest percentage of moderate or heavy events (23%). Though receiving less annual precipitation than Tromsø, Trondheim exhibited a greater number of rain events (about 167 versus 133 per year). This is probably at least in part because a larger percentage of precipitation in Tromsø is in the form of snow. Trondheim had the lowest number of moderate or heavy observations of the four weather stations examined here, with 17 per year (or 10% of the Trondheim average yearly total).

The relative frequencies of rainfall events versus wind direction (in 10° increments) for each station are shown in Figs. 2a–d. The values shown are the percentages as a function of the total number of observations coded as rain in the analysis period at each station. If the frequencies shown in the figure are thought of as percentages, then, the sum over all directions plus the percentage of rain events with no wind, at each station, will equal 100. This is just a simple way of expressing how often the wind was blowing from a particular direction when rain was observed at a station.

Interestingly, the distribution pattern is distinctly different for each station. Bergen and Tromsø are perhaps the most striking, with 58% of events in Bergen associated with a wind from the sector 130° to 170° (where 180° is due south and 90° is due east) and 53% of the events for Tromsø with wind from the sector 190° to 230°. Otherwise, particularly in Bergen, there are proportionally very few events from other directions at these stations, with the exception of the hint of a secondary maximum from 300° to 330° in Fig. 2b. Rather surprisingly in fact, there were less than 10 rain observations recorded at the Bergen station with a wind from 10°, 20° or 30°. This is in contrast to almost 1500 observations in the 30-year period with a wind direction from 150°. Similarly, in Tromsø, there were less than 10 rain observations recorded with a wind direction from 100°, 110° and 130°, while there were 639 from 210°. At both Oslo and Trondheim there is a clear directional dependence that is perhaps more pronounced at Trondheim. A westerly wind direction defined by the sector 230° to 300° was associated with 56% of the rain observations at the Trondheim airport. A small secondary maximum occurred with a wind direction slightly north of east, between 80° and 130°. Otherwise in Trondheim there were few rain observations with wind

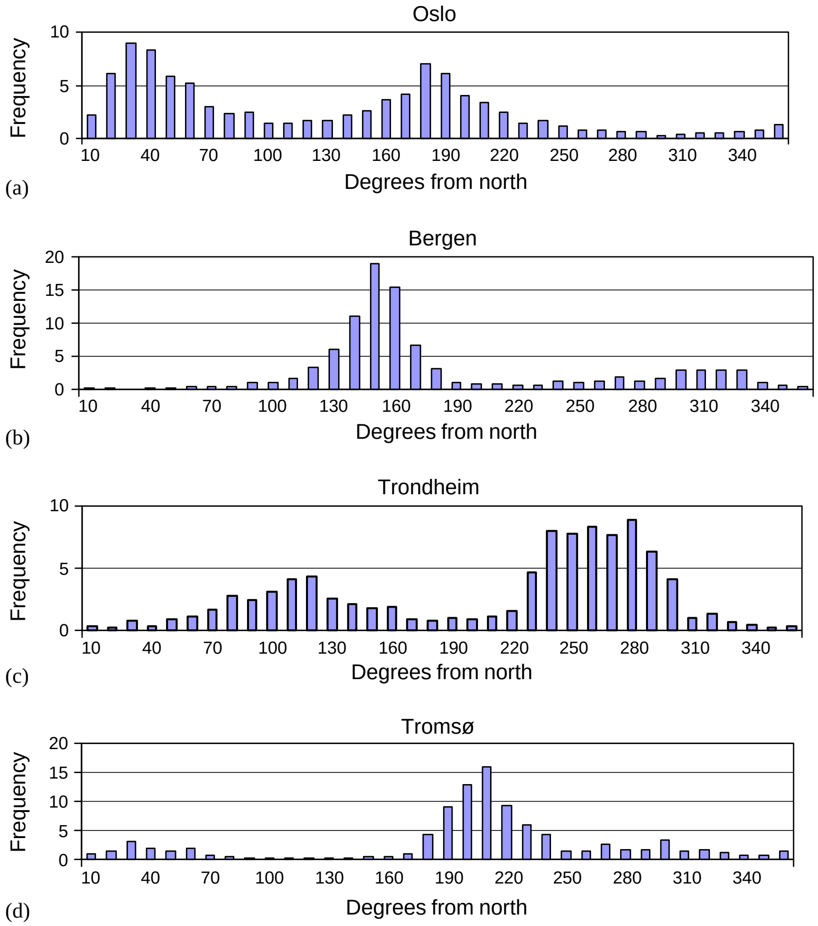

Fig. 2. Relative frequency vs. wind direction of observations coded as rain for the period 1974–2003 for (a) Bergen, (b) Trondheim, (c) Oslo and (d) Tromsø.

from the north (from about 310° to 60°) and also from the south (from about 170° to 220°). In Oslo, maxima occurred from a direction slightly east of north, from the sector 20 to 60°, and to a slightly lesser degree from a sector in the southerly direction, bounded approximately by 160° and 200°. Otherwise, there were relatively few rain observations with wind from the west and northwest (from about 250° to 350°).

The next step was to convert the frequency distributions in Fig. 2 into directional rainfall totals. Though percentages of rainfall events coded as moderate or heavy, shown in Table 3, vary somewhat from station to station, the relative frequency versus wind direction at each station is very similar to the normalized frequency distribution of total rainfall events at each of these stations. To illustrate this point, a comparison of the relative frequencies of observations coded as moderate or heavy (codes 62–65, 81 and 82) with those coded as some type of rain (codes 60–65 and 80–82) for Bergen is shown as an example in Fig. 3. The moderate/heavy values for each angle are normalized by the total number of moderate/heavy codes observed in the period, and the 'all types' values are taken from Fig. 2b. This figure suggests perhaps a slightly higher incidence of moderate/heavy events from the principal direction at Bergen (130°–170°, as discussed above), which might indicate a need for an incrementally stronger weighting of rainfall from that direction than is obtained from Fig. 2b. This is also evident in the principal directions at Tromsø and Trondheim, and from the southerly direction in comparison to the northeasterly direction at Oslo, but the differences in all cases are small. Use of the frequency distributions in Fig. 2 for decomposing average annual rainfall amounts into directional rainfall totals at each of the stations, therefore, is probably a reasonable approximation.

For driving rain considerations it is important to distinguish between liquid and solid precipitation. While annual precipitation is recorded at literally hundreds of stations around the country, the percentage of precipitation falling as rain is not. For stations where snowfall is not common, this is not a problem. At many stations in Norway, however, precipitation in frozen form represents a substantial percentage of the annual total. For the stations considered here, Bergen has the lowest relative occurrence of snowfall and Tromsø the

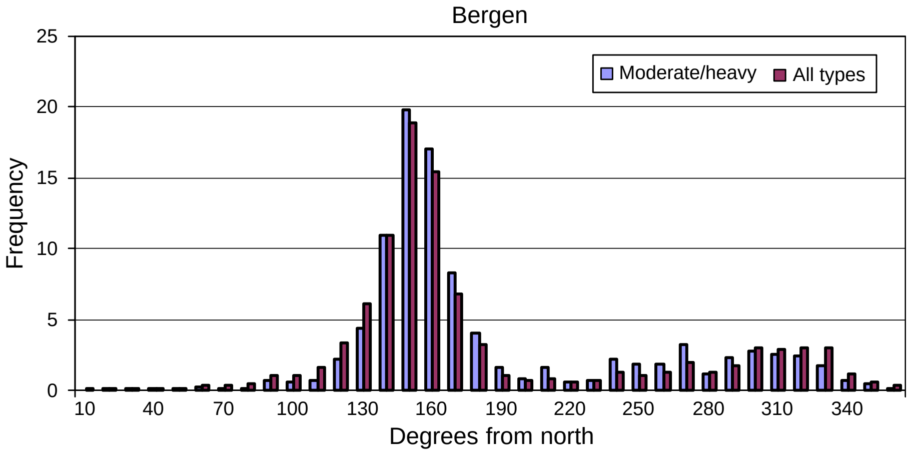

Fig. 3. Relative frequency of observations coded as moderate or heavy and observations coded as some form of rain vs. wind direction for the period 1974–2003 at Bergen.

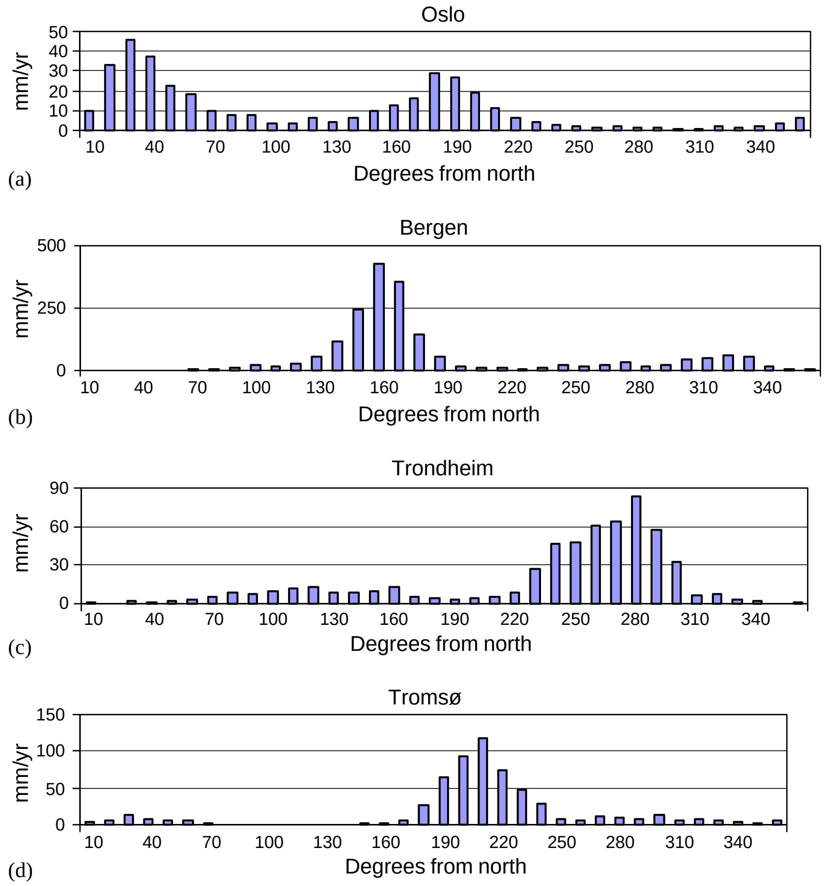

Fig. 4. Driving rain (in mm/yr) vs. wind direction for the period 1974–2003 for (a) Bergen, (b) Trondheim, (c) Oslo and (d) Tromsø.

highest proportion of the annual precipitation total. We have estimated the total annual rainfall values to be 550, 2050, 650 and 700 mm, respectively, for Oslo, Bergen, Trondheim and Tromsø.

Multiplying directional rainfall values by the respective average wind speeds during rainfall events for each wind direction yielded a measure of the directional driving rain amount at each station. This methodology is almost identical to that used by Lacy in his pioneering articles on driving rain in the 1960s [6,7]. He used the product of total annual precipitation and average wind speed (not average wind speed during rainfall, which was unavailable at that time) to create a scalar-value driving rain index, and present weather observations to develop driving rain roses showing relative directional dependence at different stations. Lacy, however, stopped short of combining the two into a single index that could be used to quantitatively compare directional dependence at different locations.

Multiplying directional rainfall by wind speed yields a driving rain index that is expressed in units that are not intuitive (Lacy used m^2/s, for example). Lacy found, in a study of 75 rainfall events over a 16-year period, that $1\,m^2/s$ corresponded to 0.206 m (or 206 mm) driving rain on a vertical surface [7]. We have adopted this conversion factor in the presentation of our driving rain data below. Directional driving rain totals for the four stations are shown in Figs. 4a–d. As the directional dependence of the mean wind speed is relatively small, and the mean wind speeds at the four stations considered here are roughly comparable, the distributions shown in Fig. 4 are qualitatively quite similar to those shown in Fig. 2.

Next, we used the data in Figs. 4a–d to calculate a driving rain wall index (I_θ) for any direction θ (which represents the angle between north and a line normal to the wall):

$$I_\theta = 0.206 \sum_D v_D r_D \cos(D - \theta), \tag{1}$$

where I_θ is expressed in mm/yr, 0.206 is the conversion factor (in s/m) from Lacy [6], discussed above, v_D is the average annual wind speed (in m/s) from direction D, r_D is the average annual rainfall (in mm) with wind from direction D, D is the wind direction (angle from north).

The summation is taken over all angles D representing a wind blowing against the wall (This includes the sector from $\theta - 80°$ to $\theta + 80°$.) Note: We do not apply the 8/9 exponent to the r_D term in Eq. (1), commonly done when calculating driving rain intensities from hourly rain and wind data [3,4], because an exponential dependence has not been shown to be valid for rain data expressed as average annual values. The results from the four stations are shown in Figs. 5a–d.

4. Comparison with earlier work

As Hoppestad's work [2] is still the only nationwide driving rain compilation available in Norway, it is

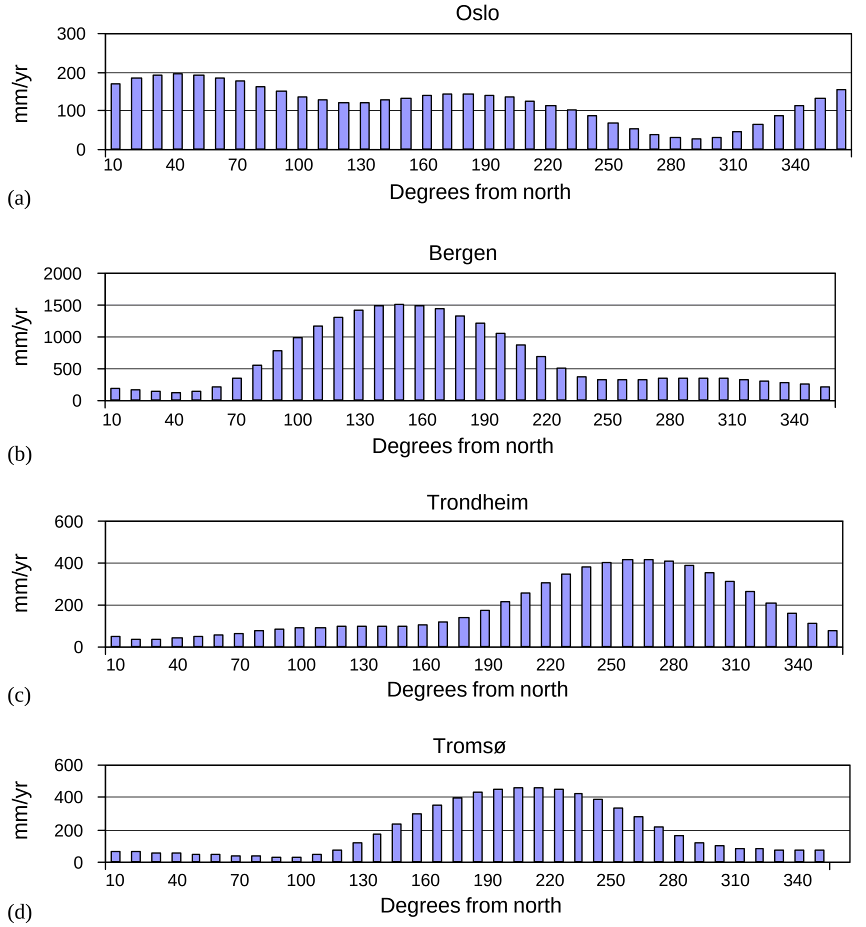

Fig. 5. Driving rain wall index (I_θ (mm/yr)) vs. wind direction for the period 1974–2003 for (a) Bergen, (b) Trondheim, (c) Oslo and (d) Tromsø.

Table 4
Driving rain values (in mm/yr) from Hoppestad (1955) compared against driving rain wall indexes, I_θ (mm/yr), for Oslo, Bergen, Trondheim and Tromsø for the analysis period 1974–2003 (in italics)

Location	Annual driving rain by direction								Total annual driving rain
	North	I_{360}	East	I_{90}	South	I_{180}	West	I_{270}	
Oslo	163	*153*	163	*149*	116	*142*	47	*39*	489 (*483*)
Bergen	157	*210*	120	*772*	1129	*1328*	688	*323*	2094 (*2633*)
Trondheim	84	*75*	53	*81*	91	*140*	301	*417*	529 (*713*)
Tromsø	51	*68*	22	*30*	202	*349*	174	*277*	449 (*724*)

interesting to compare those results with our own for these four stations. Driving rain numbers from Hoppestad for Oslo, Bergen, Trondheim and Tromsø are shown in Table 4. Note that the built environment around the stations in the late 1940s was likely to be significantly different than today, and the Bergen and Trondheim observing stations in Hoppestad were not in exactly the same locations in these cities as the observations used in this study. Some differences are therefore to be expected. For comparison with our values, it is appropriate to use the wall indexes (I_θ's) from 90°, 180°, 270° and 360° to represent driving rain from the east, south, west and north, respectively. The annual driving rain totals from 1946 to 1950 (in mm/yr) shown in Table 4 are roughly similar (at about 500 mm/yr) for Oslo, Trondheim and Tromsø, with approximately four times as much in Bergen (at just under 2100 mm/yr). With the exception of Oslo, our values (obtained by summing the four directional values in each row) are somewhat higher than Hoppestad's.

We must be cautious, however, in trying to draw any firm conclusions about absolute driving rain totals derived from these methods at any given station. It is the relative magnitudes of driving rain values versus direction at and between stations that are relevant in this comparison. The relative magnitudes between stations shown in Table 4, then, could suggest that Oslo has comparatively less total annual driving rain than is implied by Hoppestad's results. The relative magnitudes for total annual driving rain at Bergen, Trondheim and Tromsø are, however, quite similar in both studies. Furthermore, the directional dependence at Oslo is also very similar in both cases, with perhaps a slightly larger component from the south in our work. For Bergen, the 1974–2003 data yielded a relatively greater contribution from the east and less from the west than is found in Hoppestad. For Trondheim and Tromsø, the relative directional dependences were qualitatively very similar in the two studies.

5. Recommendations for further work

One important goal of future work is to determine how differences in free wind-driven rain loads affect moisture uptake in walls with ventilated wooden cladding. This is a necessary element in incorporating a driving rain wall index into design guidelines for buildings in Norway. Research to address this question is currently in progress at NBI/NTNU's experimental building site in Trondheim. Data on driving rain and moisture uptake are obtained from several instrumented test walls with different ventilated wooden cladding configurations. An automated weather station and driving rain gauge provide supporting weather data.

A second goal of future work is to develop simple algorithms for assessing how local topographical characteristics, especially in hilly or mountainous coastal terrain, alter driving rain exposures determined from observational data at weather stations. This is an important element in putting into practice use of regional driving rain information at specific building sites away from the locations where the data are gathered.

A third goal of future work is to use the method to evaluate changes in driving rain loads due to climate change under global warming. In order to do this, we must incorporate data from climate change scenarios into the methodology.

This paper is a part of the NBI Research & Development programme "Climate 2000" [8,9]. An important aspect of the programme will be the preparation of a thorough overview of the relevant climatic loads that should be taken into account during the planning, design, execution, management, operation and maintenance of the built environment. The "robustness" of the Norwegian building stock will also be addressed as part of the programme, including the development of methods for classifying different climatic parameters and their impact on building enclosure performance.

6. Conclusion

The principal advantages with the presented method are that the angular distributions of driving rain loads obtained are high resolution in terms of wind direction and that the results are based on long-term series of climate data that are readily available. Where Hoppestad yielded driving rain intensities in only four principal directions (north, south, east and west), the method described here, with 36 directions, gives a much more detailed picture of the directional dependence of wind-driven rain at a weather station. And where the Hoppestad results were based on only 5 years of data, driving rain indexes presented in this paper are from 30 years of synoptic observations representing the most recent climate.

As automated weather stations recording hourly values of precipitation and wind are becoming increasingly common in Norway, the ability to determine driving rain wall indexes on a national scale using ISO-15927-3 from long-term series of weather records will become a possibility only in the decades to come. In the meantime, the methodology presented in this paper provides a way forward, bridging the gap between Hoppestad and an international standard that is, at present, not amenable to use in Norway.

Acknowledgements

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Effects of wind exposure on roof snow loads

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Abstract

This paper presents results from an investigation of the suitability of the exposure coefficient as defined in ISO 4355 ”Bases for design of structures – Determination of snow loads on roofs”, based on thorough analyses of weather data from 389 weather stations in Norway for the reference 30-year period 1961-1990. First, the historical background of the exposure coefficient is examined. Field investigations of snow loads on the roofs are also evaluated. Next, values for the exposure coefficients in Norway are calculated according to ISO 4355. Finally, possible approaches aiming at improving calculations of wind exposure on roof snow loads are suggested. It is shown that the exposure coefficient as defined in ISO 4355 does not reflect the actual effects of wind exposure on roof snow loads in Norway, the main reasons being oversimplifications in the definition of the coefficient and the extreme variations of the climate in Norway. The definition is based on coarse simplifications of snow transport theories, and must be revised and improved to serve as an applicable tool for calculations of design snow loads on roofs in Norway.

Keywords: buildings, roofs, snow, snow loads, structural design, wind loads.

1. Introduction

In the current Norwegian snow load standard NS 3491-3 “Design of structures - Design actions - Part 3: Snow loads” [1] snow loads on roofs are defined as

$$s = \mu \cdot C_e \cdot C_t \cdot s_0 \qquad (1)$$

where s_0 is snow loads on the ground. The parameters μ, C_e and C_t describe conditions on the roof. The exposure coefficient C_e takes into account that wind removes snow from flat roofs. Using this coefficient the snow load on a sheltered roof becomes twice as large as the snow load on a windswept roof. The shape coefficient μ describes the distribution of snow load on the roof due to geometry. The thermal coefficient C_t defines the reduction of the snow load on the roof as a function of the heat flux through the roof. An equivalent

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expression can be found in ISO 4355 ”Bases for design of structures – Determination of snow loads on roofs” [2].

In practice, it has turned out difficult for consultants in structural engineering to determine the exposure coefficient C_e. The main reason is the meteorological input needed. According to an informative annex in ISO 4355 and NS 3491-3, the exposure coefficient is a function of the mean temperature, θ, in the coldest winter month and number of days, N, with a wind velocity above 10 m/s where N is defined as an average for the three coldest months of the year (see Table 1). Mean values for “many years” are recommended (usually 30 years). This meteorological information is available merely at advanced weather stations. If a building site happens to be located near such a station, the data needed is still not easily accessible.

Table 1. Exposure coefficient according to ISO 4355

Winter temperature		**Winter wind category**		
Category	Mean temp. (ºC)	I $N < 1$	II $1 \leq N \leq 10$	III $N > 10$
A	$\theta > 2.5$	1,0	1,0	0,8
B	$-2.5 \leq \theta \leq 2.5$	1,0	0,8	0,6
C	$\theta < -2.5$	0,8	0,8	0,5

In this paper weather data from meteorological stations in Norway for the reference 30-year period 1961-1990 is used to determine the exposure coefficient C_e according to the definition in ISO 4355. First, historical field investigations studying snow loads on roofs are evaluated giving the background of the exposure coefficient. Next, values for the exposure coefficients are calculated for 389 meteorological stations, and the suitability of the definition in order to describe the effects of wind exposure is discussed. Finally, possible approaches aiming at improving calculations of wind exposure on roof snow loads are suggested.

2. Background

2.1. Snow load on roofs according to ISO 4355

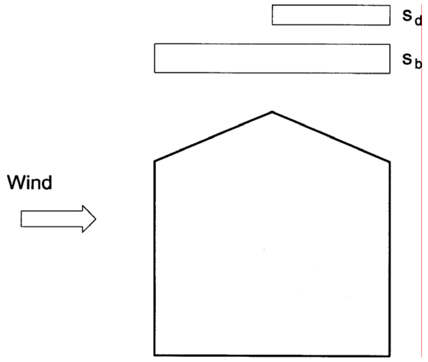

Fig. 1. Balanced snow load s_b and drift snow load s_d on pitched roofs.

In ISO 4355 ”Bases for design of structures – Determination of snow loads on roofs” [2] the snow load on the roof is defined as the sum of a balanced load s_b, a drift load part s_d and a slide load part s_s (see Fig. 1):

$$s = s_b + s_d + s_s \qquad (2)$$

The balanced load s_b is uniformly distributed on the roof (except for curved roofs) and a function of characteristic snow load on the ground s_0, exposure coefficient C_e, thermal coefficient C_t and slope reduction coefficient μ_b:

$$s_b = s_0 \cdot C_e \cdot C_t \cdot \mu_b \qquad (3)$$

The slope reduction coefficient, μ_b, defines the reduction of the snow on the roof due to roof slope and surface material. High slopes and smooth surface materials make the snow slide from the roof. In Fig. 2 slope reduction coefficient μ_b is shown for a single pitched roof with non-slippery surface.

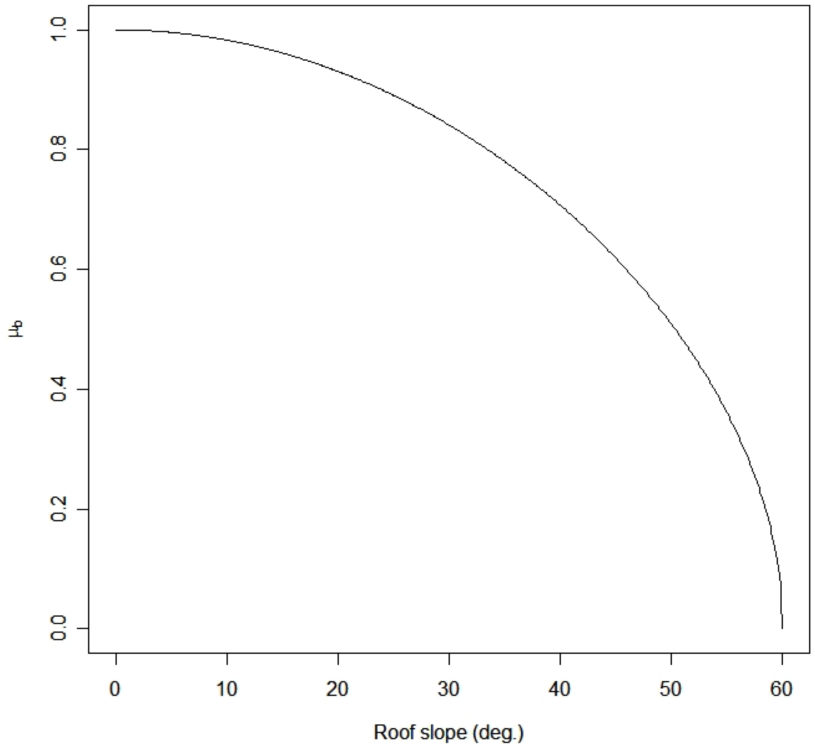

Fig. 2. Slope reduction coefficient μ_b for simple pitched roofs with non-slippery surface.

The thermal coefficient C_t defines the reduction of the snow load on the roof as a function of the heat flux through the roof, causing snow melting.

The exposure coefficient C_e defines the balanced load on a flat horizontal roof of a cold building, as a fraction of the characteristic snow load on the ground. The coefficient includes the effect of snow being removed from flat roofs by wind. According to an informative annex it is a function of the mean temperature, θ, in the coldest winter month and number of days, N, with a wind velocity above 10 m/s (N is an average for the three coldest months of the year). See Table 1.

In addition to the balanced load s_b, a drift load part s_d has to be included in order to take into account snow accumulation on leeward side of the roof due to drifting. The drift load s_d is a function of characteristic snow load on the ground s_0, exposure coefficient C_e, thermal coefficient C_t, slope reduction coefficient μ_b and drift load coefficient μ_d:

$$s_d = s_0 \cdot C_e \cdot C_t \cdot \mu_b \cdot \mu_d \quad (4)$$

The drift load coefficient μ_d multiplies with μ_b and defines the amount and distribution of additional load on a leeward side or part of a roof. The coefficient depends on wind exposure and geometry of the roof. In Fig. 3 the multiplication $\mu_b \cdot \mu_d$ for various exposure coefficients C_e is shown for a single pitched roof with non-slippery surface.

The slide load s_s take into account slide from an upper roof onto a lower roof, or a lower part of a roof.

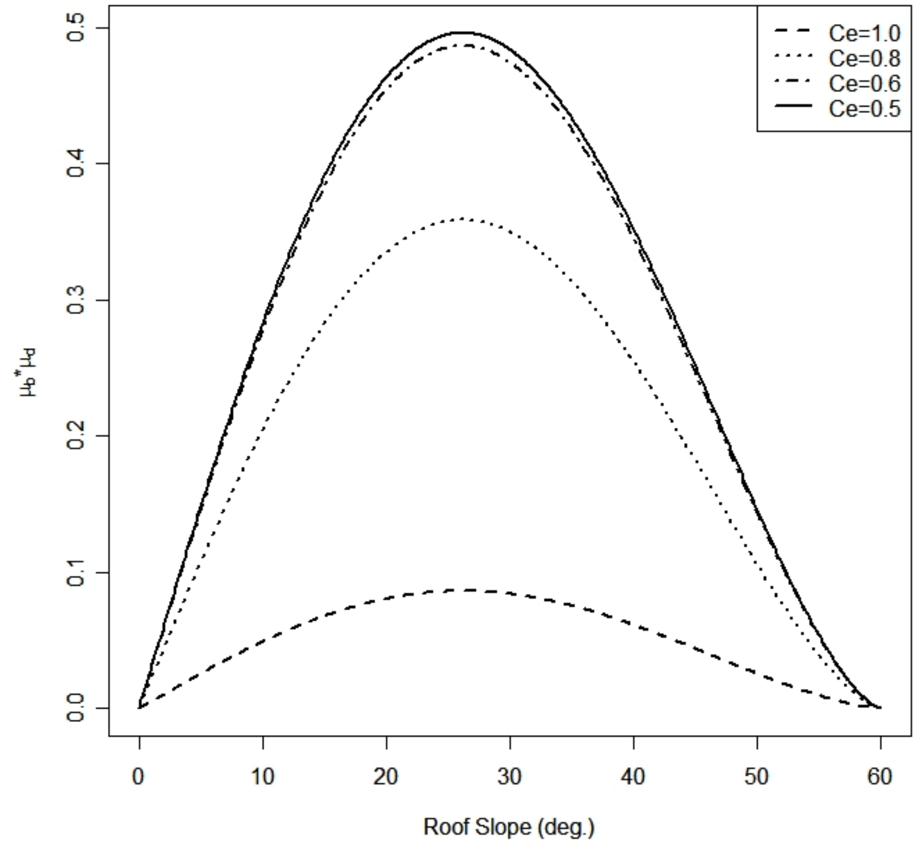

Fig. 3. Drifted shape coefficients $\mu_b \cdot \mu_d$ for simple pitched roofs with non-slippery surface.

2.2. The historical background of the exposure coefficient

In the period 1956 to 1967, the National Research Council of Canada established more than 50 observation stations across Canada, where snow depth and density measurements were registered once a week and immediately following major snowfalls on the ground and for a variety of roofs and wind exposures [3]. The roofs were both flat and sloped and varied in size. The survey concluded that the roof-to-ground ratios depend primarily on the degree to which a roof is sheltered from wind. Well-sheltered roofs had ratios up to approximately 0.9, whereas nearly all unobstructed roofs had ratios of less than 0.6. Well-exposed, unobstructed roofs in generally open areas had ratios of less than 0.3. Lutes do not discuss whether heat loss is included in these results.

Otstavnov [4] presented a method where average wind velocities for the whole winter season were used in order to describe snow drifting from flat roofs during snowfall. Experiments were performed on flat roofs and an expression for the roof-to-ground conversion factor was developed (effect of heating was excluded). In addition, an expression was developed for the total amount of snow drifted from the roof between snowfalls. This amount was found to be a function of the average wind velocity between snowfalls and the summarized time this kind of drifting occurs during the winter season. Otstavnov reported a close correlation between the number of days with snowfall and the total ground snow load.

In the period 1966 to 1986 professor Høibø at the Agricultural University of Norway measured snow depths and densities on cold pitch roofs on approximately 200 agricultural buildings in Norway [5]. The measurements were performed at the assumed maximum seasonal roof load. A total of 1300 measurements were done. Measurements were also performed in “undisturbed” areas close to the buildings. The effect of wind was not evaluated. Based on his observations, Høibø proposed roof-to-ground conversion factors for both leeward and windward side of the roof depending on roof angle and ground snow load. The magnitude of the ground snow load was found to affect the conversion factor strongly. A ground snow load equal to 1.0 kN/m^2 gave a conversion factor of respectively 0.75 and 0.82 for windward and leeward side of the roof. A ground snow load equal 3.5 kN/m^2 produced a conversion factor of respectively 0.48 and 0.62 for windward and leeward side. These formulas were restricted to buildings with ground snow load equal 3.5 kN/m^2 or less and buildings not fully sheltered.

After heavy snowfalls in the winter of 1975-76, snow depths and densities were measured at 55 pitched roofs (roof angles 18° – 25°) in Trondheim, Norway [6]. The snow was measured at 6 - 12 points at the most heavily loaded roof side. In addition, snow load was measured on the ground at 94 locations in the area of Trondheim. The roofs were anticipated to be cold roofs. The authors of this paper have calculated an average roof-to-ground ratio of 0.27 for windswept areas (based on the data from Løberg). For sheltered areas the average roof-to-ground ratio is calculated to 0.55.

Taylor [7] performed a survey of snow loads on roofs of arena-type buildings in Canada. Data were collected for 32 curved roofs and 16 gable roofs through a 4-year pilot study of snow on buildings, case histories and newspaper reports (snow events in the period 1956-77). It was concluded that the maximum of the uniformly distributed loads for both gable and curved roofs, sheltered from wind, was approximately 80 % of the specified 30-year return ground load. Five of these buildings were reported to be unheated. The effect of heat loss was not considered separately.

In case studies performed by O’Rourke [8], roof and ground snow loads were measured for 199 buildings in Northeast, Midwest and Northwest USA, during three winter seasons in the period 1975-78. A total of 253 roofs were measured. Conversion factors defined as the ratio between the maximum roof load and the maximum ground load were calculated. Areas with infrequent snowfalls and small accumulations were reported to have higher ground-to-roof conversion factors than colder areas with substantial ground snow accumulation. Average conversion factors were calculated to be 0.78 for the sheltered roofs, 0.59 for the semi-sheltered roofs and 0.53 for the windswept roofs when the effects of roof slope and heating were included. Based on this study, the average ground-to-roof conversion factors for unheated flat roofs are recalculated by the authors of this paper to be 0.76 for the sheltered roofs, 0.57 for the semi-sheltered roofs and 0.55 for the windswept roofs.

In the European Snow Load Program 1997-1999, roof snow load were measured for 55 pitched roofs and 26 flat roofs in Switzerland, Italy, Great Britain and Germany in the winter season 1998-99 [9]. The roof-to-ground ratio for flat roofs was calculated to 0.90 for sheltered roofs, 0.74 for semi windswept roofs and 0.58 for windswept roofs. When selecting the buildings for this project, unheated or very high isolated roofs were required (whether this requirement is met is not considered). The findings of the investigations, which indicate the effect of wind blowing snow from the roof, are summarized in Table 2.

Table 2. Exposure coefficients for flat roofs

Reference	**Exposure coefficient**		
	Sheltered	Semi-sheltered	Windswept
Otstavnov (1989)[a)]	0.98	0.72	0.46
Lutes (1970)	0.90	0.60	0.30
Taylor (1979)	0.80[b)]	-	-
O'Rourke (1983)[c)]	0.76	0.57	0.55
Høibø (1988)			
$s_0 = 1.0$ kN/m^2	0.82 [d)]	-	-
$s_0 = 3.5$ kN/m^2	0.62 [d)]	-	-
Løberg (1976)	-	0.55	0.27
Com. Eur. Comm (1999)	0.90	0.74	0.58

a) Assumed snow cover for 3.5 months. Average winter wind velocity in sheltered, semi-sheltered and windswept area are assumed to be respectively 2 m/s, 4 m/s and 6 m/s
b) Snow ground load with 30-year return period is used when calculating roof-to-ground ratio
c) Values are recalculated in order to apply unheated roofs
d) Degree of wind exposure is not registered. s_0 – ground snow load.

In investigations performed by Irwin et al. [10], the effect of roof size was studied. It was concluded that there is a trend towards increased uniform snow loads on flat roofs with increasing size. It was recommended to account for roof size when considering roofs with characteristic lengths above respectively 75 m and 200 m for sheltered and open wind exposure (characteristic length equals width * (2 – width/length)).

ISO 4355 defines wind categories and temperature classes in connection with determination of the exposure coefficients C_e. The justification of the recommendations is somewhat vague. According to Otstavnov [4] drifting occurs at average wind velocities above 4 m/s during snowfall and above 6.5 m/s with no snowfall. Other studies have focused on a more instant threshold wind velocity and not a wind velocity averaged over a longer period.

According to Mellor [11] threshold wind velocities of 3 to 8 m/s at a height of 10 m are needed in order to transport loose and unbounded snow. If the surface snow is densely packed and firmly bounded threshold wind velocity above 30 m/s may occur.

According to Kind [12] the threshold wind velocity is approximately 5 m/s at a height of 10 m for fresh dry snow, 11 m/s for slightly aged or hardened snow and 23 m/s for snow hardened by very strong winds.

Li and Pomeroy [13] evaluated hourly observations from the period 1970 to 1976 at 16 meteorological stations in the Canadian prairies. Based on this studies threshold wind velocities were recorded and presented as a function of temperature. It was concluded that threshold wind increased nonlinearly with ambient air temperature above –25 °C. An average threshold wind velocity of 9.9 and 7.7 m/s was observed for respectively wet and dry snow transport. An average threshold wind velocity of 7.5 and 8.0 m/s was observed for respectively fresh and aged snow.

Results from field investigations show a reduction in roof snow load with increasing wind exposure (Table 2). The values of the exposure coefficients vary, possibly as a result of differences in the definitions of the categories. Although it can be concluded that wind exposure is of large importance for the resulting snow loads on roofs.

3. The exposure coefficients for Norway according to ISO 4355

Data from 389 meteorological stations in Norway is used in order to derive temperature zones and wind categories as defined in ISO 4355. Within the normal period (1961 – 1990), stations with at least 15 years of data are used. Temperature zones are based on reference grids for the normal period developed by the Norwegian Meteorological Institute. As seen on Fig. 4, almost none of the stations have mean temperatures above 2.5 °C in the coldest winter month. Temperature category A (as defined in ISO 4355) is only represented at small offshore islands in the southern part of Norway, and it is therefore not visible on the map in Fig. 4. Mean temperatures between –2.5 and 2.5 °C are mainly found in the coastal areas in south and west. For a majority of the stations, mean temperatures below –2.5 °C are registered for the coldest winter month.

Almost none of the meteorological stations situated in the zone with mean temperatures between –2.5 and 2.5 °C have less than one day with wind velocity above 10 m/s. In south and west, stations situated at places highly exposed to wind (e.g. at lighthouses on islands/peninsulas) have more than 10 days with wind velocities above 10 m/s. In areas settled with buildings, the number of days with wind velocities above 10 m/s is mainly between 1 and 10. In the northern part of Norway, the number of days with wind velocities above 10 m/s exceeding 10 days is found for this temperature zone also in settled areas.

Considering the areas with mean temperatures below –2.5 °C in the coldest winter month, some characteristics can be observed. In the inland of southern Norway, the stations situated in the mountainous areas have mainly between 1 and 10 days with wind velocity above 10 m/s in the three coldest winter months. For lower regions, where most of the people are settled, the number of days with wind velocity above 10 m/s is mainly below 1. Further north the number of days with wind velocity above 10 m/s is mainly between 1 and 10 days. At some of the stations highly exposed to wind, the number of days with wind velocity above 10 m/s exceeds 10 days. These stations are mainly situated in areas close to the sea where the building density is low.

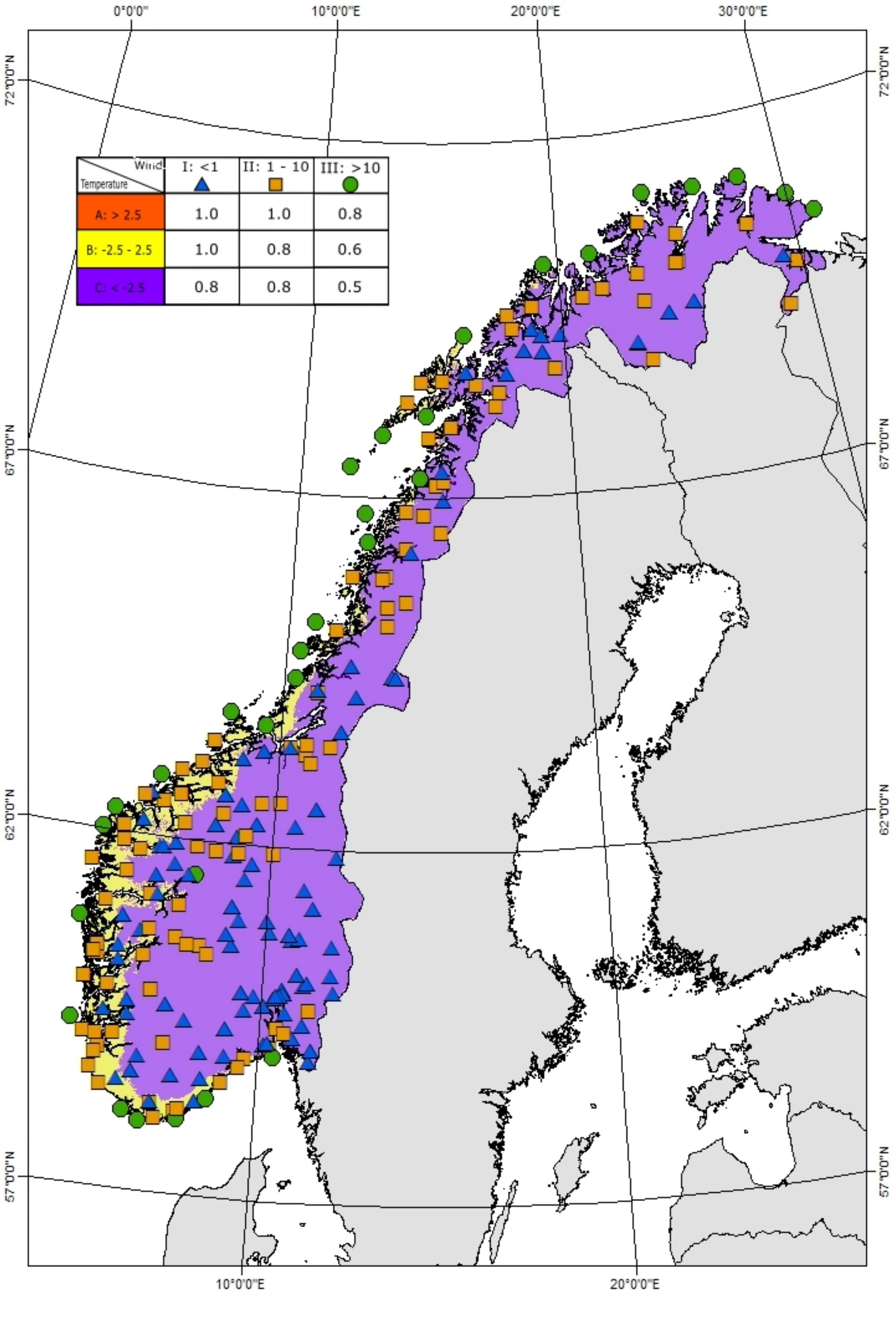

Fig. 4. Winter temperature categories and winter wind categories as defined in ISO 4355 for 389 meteorological stations (weather data from the reference 30-year period 1961 – 1990). See also Table 1 for explanation.

In Fig. 5 the exposure coefficients (according to ISO 4355) for 389 meteorological stations are presented. For 85 % of the meteorological stations the exposure coefficient is 0.8, for 8 % the value is 0.6, for 6 % the value is 1.0 while for 2 % the value is 0.5.

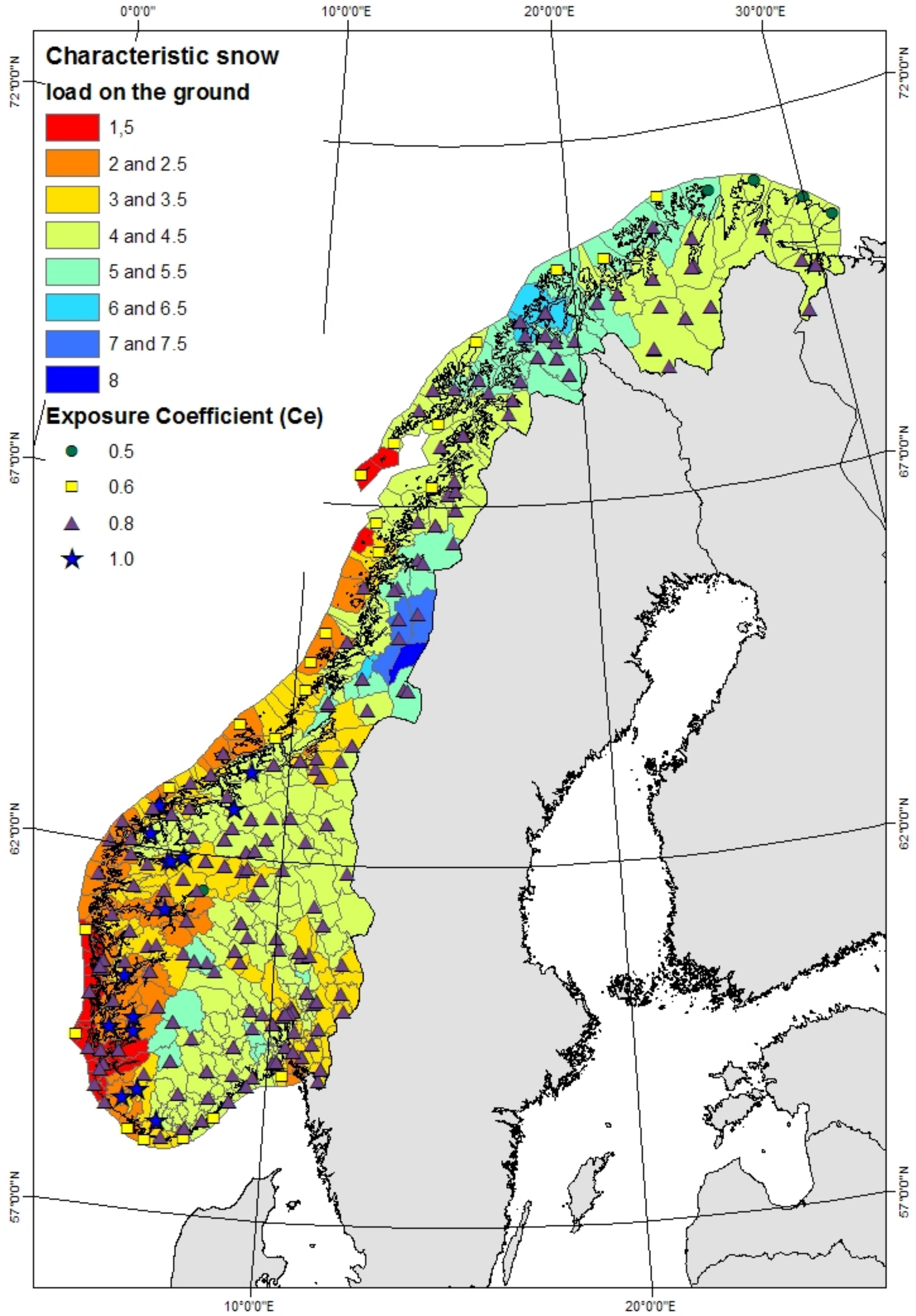

Fig. 5. Exposure coefficients for 389 meteorological stations (weather data from the reference 30-year period 1961 – 1990) and characteristic snow load on the ground (kN/m^2, 50-year return period) for municipality centres.

Six meteorological stations (2 %) achieve values of the exposure coefficient equal to 0.5. Two of these stations are situated in the mountains of southern Norway 1828 m and 2062 m above sea level, respectively. The other four stations are situated in the northernmost parts of Norwegian mainland, 70 degrees north at the gateway to the North-east Passage and to the Barents Sea. Three of these stations are situated at lighthouses close to the sea and exposed to the weather. Only one station is situated in a settled area: “Vardø radio” in Vardø.

30 meteorological stations (8 %) achieve values of the exposure coefficient equal to 0.6. 19 of these stations are situated at lighthouses. Seven stations are situated at small island communities on the edge of the coastline heavily exposed to the weather. Only four stations (1 %) are situated in settled areas: Ørland III, Bodø, Andøya and Loppa. None of the meteorological stations in this category is situated in the eastern part of Norway where the building density is highest.

22 meteorological stations (6 %) achieve values of the exposure coefficient equal 1.0. These stations are placed shielded from the wind typically at the farther end of the long fjords of western Norway. None of the stations in northern Norway is in this category.

331 meteorological stations (85 %) achieve values of the exposure coefficient equal to 0.8. Almost all of the stations in settled areas are found in this category. Exceptions are one station with an exposure coefficient of 0.5, four stations with exposure coefficients of 0.6 and 22 stations with exposure coefficients of 1.2 as mentioned above.

4. Evaluation of the exposure coefficients for Norway

4.1. Historical field investigations

Results from field investigations show a reduction in roof snow load with increasing wind exposure (see Table 2). The calculated values of the exposure coefficient according to ISO 4355 for building sites with mean temperature between –2.5 °C and 2.5 °C are in fairly good agreement with these results, and to the conservative side. But there is no available research supporting ISO's description of wind categories.

In regions with a mean temperature above 2.5 °C, ISO 4355 allows a reduction of the snow loads on the roof is only permitted at building sites with more than 10 days of wind velocity above 10 m/s. This seems not to be justified by field investigations. It is nevertheless reasonable considering the fact that high temperatures reduce the ability of wind actions to transport snow. Whether this temperature limit should be 2.5 °C is uncertain.

In regions with a mean temperature below –2.5 °C, ISO 4355 recommends a reduction of snow loads also when the building is completely shielded. An exposure coefficient equal to 0.8 for this situation agrees with some of the research results (see Table 2). A question remains: were the buildings in the historical investigations completely shielded? Is it possible to obtain a completely shielded building? For a completely shielded building the snow load on a flat roof is expected to be equal to the snow load on the ground.

4.2. Snow transport theories

According to snow transport theories drifting occurs even for light winds (0.3 – 1.5 m/s). At higher wind velocities (1.6 – 3.3 m/s) the snow particles move more horizontally than vertically. Drifting affects the deposition of snow; particles are transferred through areas with high wind velocities and accumulate in areas with low wind velocities. At wind velocities between 3.4 and 5.4 the snow moves considerably faster horizontally than vertically, and significant redistribution may occur. Higher winds often blow the snow off the roofs leaving them almost bare ([14], [7]).

The limit of 10 m/s chosen for the wind categories seems unreasonable considering the fact that drifting occurs at wind velocities as low as 0.3 to 1.5 m/s. A larger number of meteorological stations are expected to achieve a value of the exposure coefficient below

0.8. In Canada heavy snowfalls often coincidence with high wind velocities according to [15]. This is not the pattern in Norway. In Norway heavy snowfalls may occur at low wind velocities as well as at higher wind velocities.

4.3. The Norwegian climate

Norway is a country with large variations in mean temperatures and wind velocities. In Fig. 6 mean winter temperatures are given (December – February). There is a pattern of low winter temperatures in the mountainous regions of southern Norway and the inland regions in the far north. Coastal areas in southwest have temperatures between 0 and – 2.5 °C, while the inland in the far north has winter temperatures less than –15 °C. In Fig. 7 the number of days with wind stronger than 5 m/s for months with normal temperature less than 1 °C is presented. 1 °C was chosen as a limit to consider all months with high probability of snow and snowdrift. The map also shows number of months with normal average temperature less than 1 °C. Approximately 90 % of the Norwegian mainland has six or more months with average temperature less than 1 °C. I.e. six or more months with possible snow and snowdrift. In Fig. 7 there is a clear pattern of higher probability of high winds in the costal areas. It should be noted that the costal areas do not always have the highest number of occurrences, but these regions also have fewer months with temperatures below 1 °C. In the middle of Norway (approximately 62° – 67° north) this pattern is most pronounced. In this region the coastal areas have at least one month with mean temperatures below 1 °C less than the inland, but a higher number of days with wind above 5 m/s.

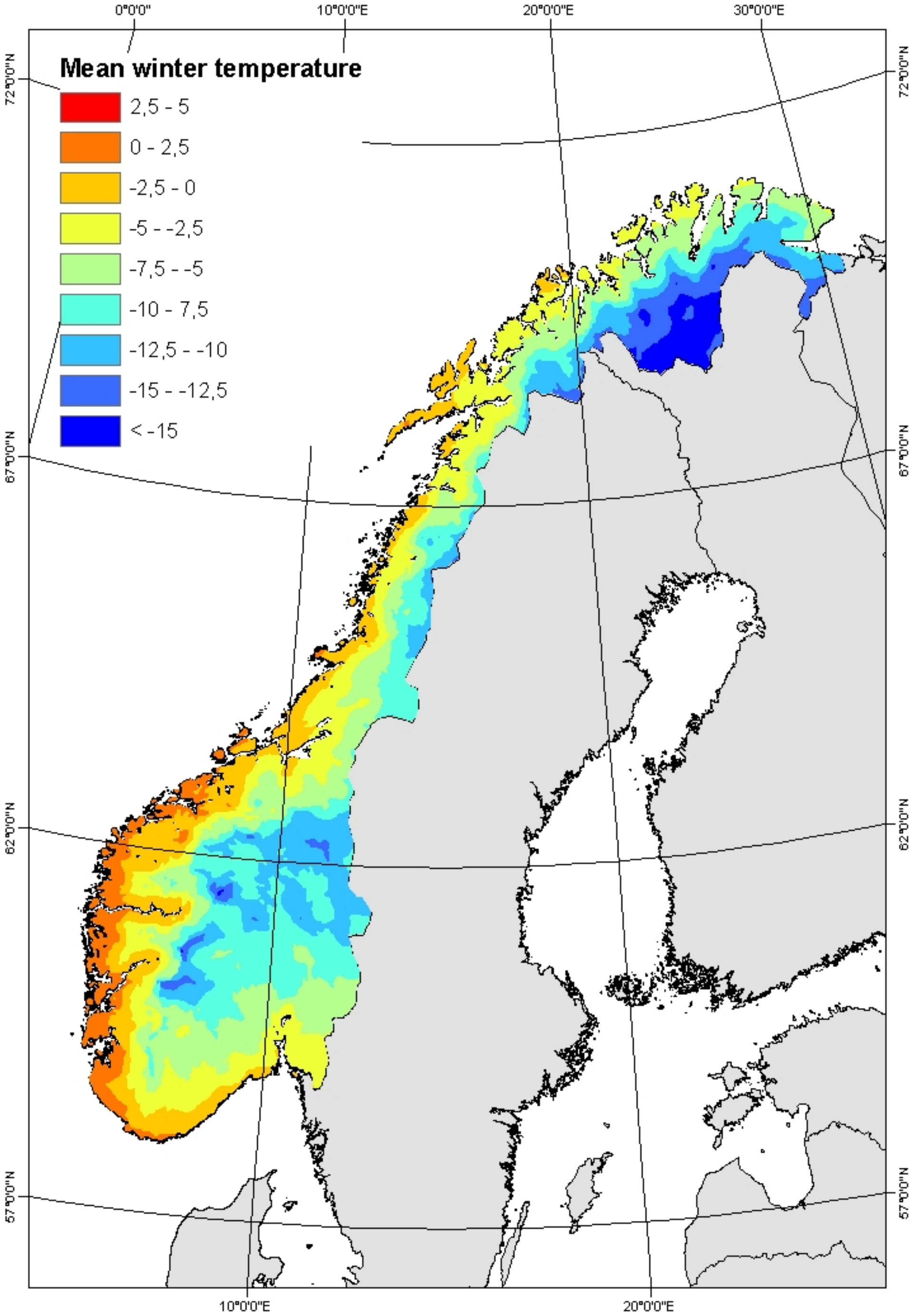

Fig. 6. Mean winter temperature (ºC, December – February, weather data from the reference 30-year period 1961 – 1990).

Norway also has large variations in snow loads (see Fig. 5). Characteristic snow loads on the ground varies from 1.5 kN/m^2 in coastal areas in the south up to 9.0 kN/m^2 in some inland areas (50-year return period).

As documented, Norway has areas with high snow loads (Fig. 5) and high frequency of wind (Fig. 7). In these areas the wind affects roof snow loads, and the exposure coefficient is expected to achieve its lowest value. As seen in Fig. 4 the definition of the exposure coefficient as given in ISO 4355 does not point out these areas as areas where wind blows snow away from roofs.

Many of the meteorological stations with an exposure coefficient of 0.8 are situated in areas exposed to wind and snow (e.g. the mountainous areas of southern Norway and stations along the coastline). Exposure coefficients lower than 0.8 was therefore expected for these stations.

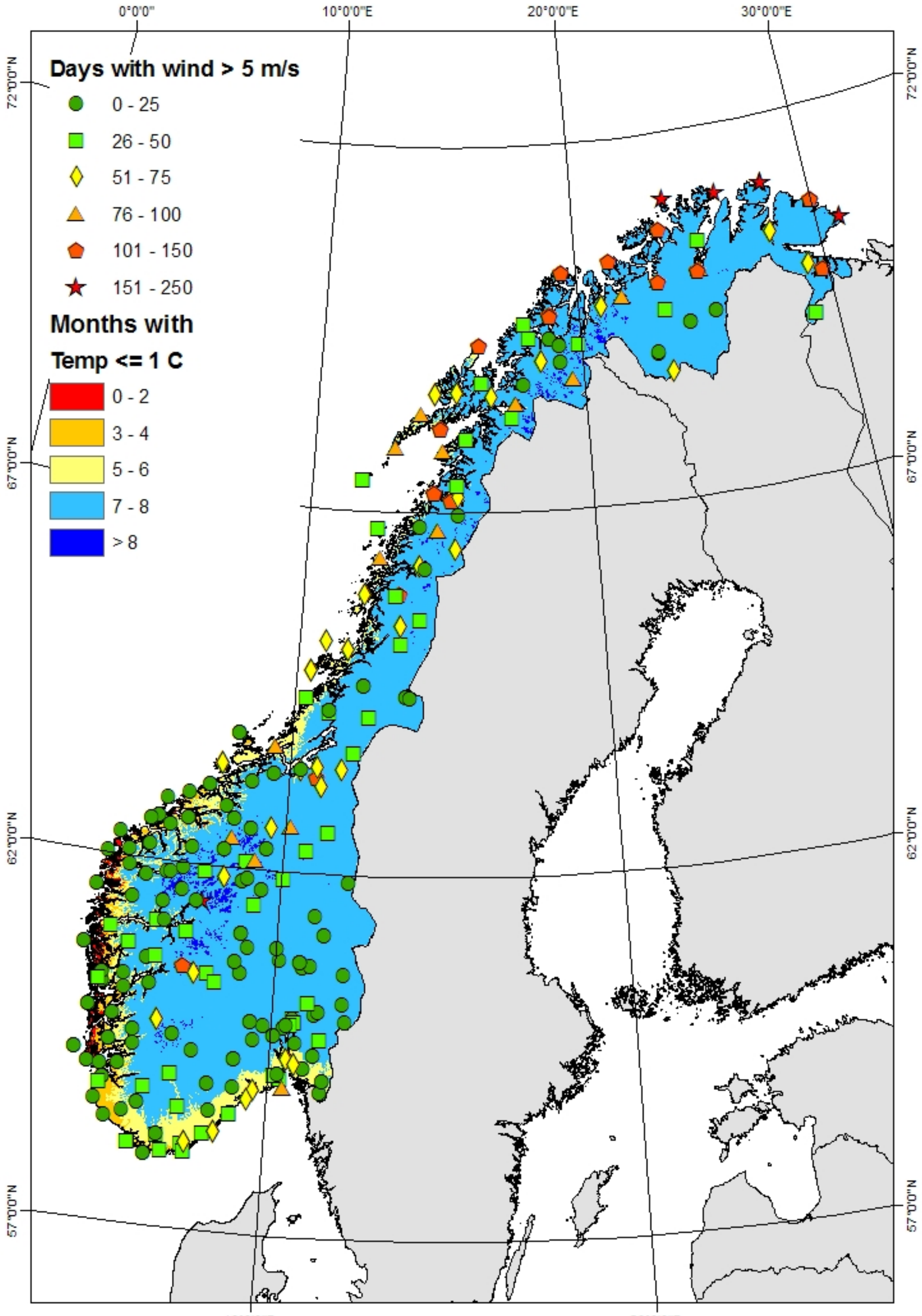

Fig. 7. Days with wind velocity above 5 m/s in months with mean temperature 1 ºC or below for 389 meteorological stations (weather data from the reference 30-year period 1961 – 1990).

4.4. Main findings

Historical field investigations show that the effects of wind on roof snow loads are of significance for a large part of buildings. According to snow transport theories snow drifting occurs even for low wind velocities. Norway has a climate with low winter temperatures, large snow amounts and high frequency of wind. The definition of the exposure coefficient found in ISO 4355 is too conservative and does not manage to differentiate the buildings in settled areas. The stations found to be most windswept are situated in areas where no or a very few buildings are located. Other stations situated in areas known as windswept and with high snowloads are found in the same category as more shielded stations. According to the definition in ISO 4355 the buildings in the field investigations of Høibø [5] and Løberg [6] have all exposure coefficient equal to 0.8 although the documentation shows exposure coefficients considerably lower for the investigated buildings.

Norway has large variations in snow loads (Fig. 5). The lowest snow loads are due to heavy snowfalls over a short period while the higher snow loads are a result of accumulation over a long winter season. It seems reasonable that areas with low snow loads have higher exposure coefficients than areas with high snow loads. This is taken into account in ISO 4355 when differentiating the exposure coefficient according to mean temperatures, but the limits chosen are not substantiated thoroughly through research results.

Another way of taking into consideration the accumulation length is to include the length of the winter season when deciding the exposure coefficient for a specific building site. In the procedure presented by Otstavnov [4] both the length of the winter season and number of days with snowfalls are included. Number of days with average wind velocities above 10 m/s in the three coldest months defines the wind category according to ISO 4355. When selecting three months, it is indirectly assumed that this is the length of the winter season. Other periods should be considered when evaluating areas with lower or higher accumulation period.

Mean temperatures for the coldest winter month are needed when determining the value of the exposure coefficient. At first thought this temperature could also be considered as a value taking into account the possibility of snow to be transported by wind actions. In this situation the actual length of the winter season should be chosen. As mentioned above it can also be a measure of the size of the snow ground load. This correlation should then be scientifically documented.

5. Discussion and further work

Meteorological stations are located to enable a good representation of regional climate. Typical locations are in agricultural and settled areas, airports and lighthouses. I.e. these areas have a better representation than mountainous regions.

Maximum snow loads on the roof often do not appear simultaneously with maximum snow loads on the ground. In the measurements reported by O'Rourke [8] maximum snow load on roofs are measured independent of maximum snow loads on the ground. In the measurements performed by Høibø [5] the roof and the ground are measured simultaneously.

It also seems reasonable that the exposure coefficients decrease as the return period of the characteristic snow loads on the ground increases. When measuring snow loads the exposure coefficients therefore are expected to be higher in a normal year compared with a year when extreme loads occur. In measurements reported by Taylor [16] snow loads on the ground with return period of 30 years are used when calculating the roof-to-ground ratio. Similar evaluation should be performed also for other measurement data, for instance the data of Høibø [5].

In Norway the meteorological data needed are not easily accessible for structural engineers. The data basis can be bought at the Norwegian Meteorological Institute, but the wind category (according to ISO 4355 [2]) has to be calculated either by meteorologists or by consultants in structural engineering. After deciding the mean temperature and wind category for the nearest meteorological station delivering such data, the structural engineer has to evaluate if these values are reasonable for the temperature and wind climate at the specific building site. Local topography including altitude, surrounding buildings and trees has to be evaluated in order to decide the wind category. High-resolution maps are required. This evaluation is time-consuming and demands high qualifications.

The investigation presented will be used as an important basis for ongoing studies within the ongoing Norwegian research & development programme “Climate 2000” [17], e.g. the relationship between snow loads on roofs and wind exposure will be further investigated [18]. In this article the suitability of the exposure coefficient as defined in ISO 4355 is analysed. Further work should focus on developing a definition reflecting the physical processes more correctly. There is for instance a need for taking into account the length of the snow accumulation. The definition of wind categories should also be looked into, and a more detailed method specifying wind exposure should be developed. The authors are now addressing these issues.

When using the exposure coefficient, the snow load on a sheltered roof becomes twice as large as the snow load on a windswept roof. The significance of this coefficient according to total building costs will be studied. To what degree could the society profit by an entirely use of this exposure coefficient? The advantage of built-in security accounting for future change in wind exposure or climatic impact could be desirable.

Methods are in the recent years being developed making it possible detailing the design processes according to design loads. In this work advanced tools and data processing are required. These tools are for many cases not available for structural engineers. Using these methods also requires high qualifications and the risk of engineers using it in an erroneous way are present. Further work should focus on developing tools for structural engineers making it possible differentiating design loads and thereby taking into account local topography and climate.

The “robustness” of the Norwegian building stock will also be addressed as part of the "Climate 2000" programme, e.g. through analysis of statistical data from the Ground Property, Address and Building Register along with knowledge on process induced building defects [19]. The lifetime of the built environment depends closely on the severity of local climate conditions, and a sensible way of ensuring high-performance building enclosures in a country with extreme variations could be to develop more sophisticated climate classifications or exposure indexes for different building materials and building enclosures. This work is now concentrated on issues related to building technology or building physics, and include development of methods for classifying different climate parameters and their impact on building enclosure performance (e.g. [20], [19]).

6. Conclusions

It is shown that the exposure coefficient as defined in an informative annex of ISO 4355 does not reflect the actual effects of wind exposure on roof snow loads in Norway, the main reasons being oversimplifications in the definition of the coefficient and the extreme variations of the climate in Norway. The definition is based on coarse simplifications of snow transport theories. It must be revised and improved to serve as an applicable tool for calculating design snow loads on roofs, using the best available data from meteorological stations in Norway.

As documented in this paper, Norway has areas with high snow loads and high frequency of wind. In these areas the wind affects roof snow loads, and the exposure coefficient is expected to achieve its lowest value. The definition of the exposure coefficient as given in ISO 4355 does not point out these areas as areas where wind blows snow away from roofs.

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