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WARM, WET AND WILD –
Climate change vulnerability analysis applied to built environment

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Main trends for the northern hemisphere towards year 2100 predict a warmer, wetter and wilder climate. Climate vulnerability analysis conducted by SINTEF and The Norwegian Meteorological Institute, show that due to increased amounts of precipitation and a warmer climate, as many as 2.4 million of today's buildings in Norway will be exposed to a high risk of rot decay in year 2100. Presently, 615 000 buildings are in this exposure category. Other climate parameters like sea level rise, wet winter precipitation, temperature fluctuations around 0°C, changes in wind patterns, changes in groundwater level, and decrease of permafrost will add to the increased strain to the built environment. A high percentage of Norwegian buildings are characterised by the use of wood in both substructures and building envelope, and at this already exposed to rot decay risks in humid areas. The built environment faces dramatic consequences if not met with adequate measures.

The paper focuses on estimation of vulnerability towards climate change impacts in the built environment of Norway. A recent climate vulnerability analysis performed by SINTEF Building and Infrastructure and The Norwegian Meteorological Institute offers a method to digitally estimate the number of buildings affected by different climate parameters, today and in the future.

This method is employed in a quantitative climate vulnerability analysis, applied to the Norwegian building stock. A calculation of the number of existing buildings being affected by different climate change parameters in a 2100 scenario is presented, with an in-dept study of rot decay. The paper will increase the knowledge of how climate change presumably will affect the present building stock. The paper forms part of two of the authors' PhD studies at the Norwegian University of Science and Technology (NTNU).

1 CONTEXT

1.1 Climate and the built environment in Norway

Main climate change trends towards year 2100 indicate a warmer, wetter and wilder climate. If thorough vulnerability analyses and profound measures are not launched to meet the challenges, the consequences for the built environment will be dramatic and radical. In this paper, consequences to the Norwegian building stock of climate change are considered and estimated on a superior level. Through climate change scenario based analyses, numbers of buildings affected and levels of severity are generated.

1.2 Main objectives and scope

Through a quantitative method, climate change parameters and possible impacts on the built environment are enlightened. The aim is to contribute to a better understanding of how climate change can be met and adapted to. By identifying areas of vulnerability, measures to increase the robustness of the built environment are suggested.

Rot decay is the parameter subject to the most thorough impact assessment evaluation in this paper, and serves as a pilot to demonstrate how other climate parameters like mean temperature, snow loads, sea level, winter precipitation, and so on can be correspondingly assessed. Risk of rot decay is thus applied as a case, to demonstrate what kind of information is possible to draw for the wanted parameters.

1.3 Methodological approach

The paper is based on a large survey performed at a national level, by SINTEF Building and Infrastructure (Øyen et al., 2010), as a basis for a governmental panel report on climate change and impact on a national level (NOU, 2010).

The quantitative method employed is described by Almås et al. (2011) and Øyen et al. (2010). Building and climate data are first compiled in a Geographic Information System (GIS). A computer model calculates the number of buildings that could be affected by different climate parameters, based on historical climate data (1961–1990) and on a specific future climate scenario (2071–2100), both at national, regional and local levels. The analyses are executed by employing existing methods for climate vulnerability and geographically differentiated building design, but the methodological composition is, to our knowledge, new.

The project was originally quite confined. The range of literary sources was thus limited. Main sources of background information has been publications from the Climate 2000 programme at SINTEF Building and Infrastructure (Lisø and Kvande, 2007), and an extract of building information from the national Norwegian Building Matrix[1] (hereafter referred to as the Matrix), former called the Norwegian Ground Property, Address and

[1] www.statkart.no

Building Register (GAB Register). The Matrix provides some information about the state of different vintages of buildings, and serves as the official property register. Climate information is drawn from the report *Klima Norge 2100* (*Climate Norway 2100*, Hanssen-Bauer et al., 2009). In addition to the main sources, the Swedish governmental panel report on climate change and vulnerability (SOU, 2007) has been applied as a bais for comparison.

The vulnerability analysis is effectuated for buildings. Other constructions, installations or infrastructures have not been subjected in the analysis. At this, climate change impacts to remaining infrastructures, water supply, sewerage, roads, bridges, electric supply mains etc., as well as agricultural infrastructures, fauna or flora, are not included in the analysis.

Rot decay risk figures on a regional level are quite accurate. For other parameters, figures on a national level are coupled with some individual regions/counties. As for landslides, flooding and sea level rise, key figures from external sources are employed. The two periods are also referred to as present situation and situation in year 2100. Projections are originally based on three different models (climate scenarios), here limited to one model (Had-A2), in order to confine the amounts of information presented in the paper (Almås et al., 2011 and Øyen et al., 2010).

Hadley/A2 (Had-A2) is an example extrapolation with the climate model *HadAm3H* and the emission scenario A2. Emission scenarios are projections of manmade emissions of greenhouse gases and particles affecting the climate, relying on assumptions of demographic, economic and technological development. Scenario A2 assumes high global population growth, and less concerns for a rapid, economic development (15 billion people in 2100, Carbon dioxide in the atmosphere is estimated at 836 ppm in 2100).

Complementary information in the discussion is based on a qualitative case study of the early stages of the building process, where different stakeholders in the building process have been interviewed[2].

2 CLIMATE CHALLENGES AND THE BUILT ENVIRONMENT

2.1 Number of buildings in different building categories

Production of new construction in Norway in 2009 has in average decreased 14 % since 2008, thus set back to approximately the same level of production as in 2005. The production of new construction and retrofit/refurbishment building projects has been quite varying. An interesting feature in the figures from Statistics Norway is that retrofit/refurbishment activities have been increasing heavily for the last two years, with a close to 10 % increase from 2008 to 2009. Such refurbishment activity increase has also earlier been registered when the economy has been tightening up. At this, it is natural to assume that the need for retrofit/refurbishment activities in existing building stock with a

[2] The qualitative case study is part of an ongoing PhD study by C.F. Øyen, at the Norwegian University of Science and Technology. Title: *Moisture-proof building process - Causalities and interaction in early stages*

focus on climate adaptation is necessary. Table 1 displays an overview of all buildings registered in Norway, by building category, for all of Norway (including Spitsbergen). The statistical material is based on an extract of building information from the Matrix. The extraction was carried out in January 2010. The Matrix also includes a digital property chart.

2.2 Key figures building statistics

- Per January 2010 3.93 million buildings are registered in the Matrix. Of these, 1.44 million (37 %) are residential buildings;
- In 2008, some more than 3.8 million buildings were registered. Of these approximately 38 % were residential buildings (130 000 net increase in two years);
- In 2008, slightly more than 2.3 million dwellings were registered; of this 1.2 million were detached houses. Nearly 80 % of Norwegian households own their dwelling;
- Around 482 000 second homes (holiday cottages/cabins) and other buildings employed as vacation homes were registered in the Matrix by January 2010;
- More than 1.2 million buildings (30 % of all registered buildings) are garages, outbuildings etc. linked to residential or second homes;

TABLE 1: Overview of total building stock, distributed by building categoriy (bundled) for all of Norway including Spitsbergen

Building category	**Total number of buildings**
1-11 small houses	1 430 365
12-20 residential blocks of flats	38 363
21-25 cabins/second homes (holiday cottages)	482 044
26-30 garages, sheds, temporary dwellings and other residential buildings	1 230 407
31-35 industrial buildings	38 859
36-38 energy supply buildings	20 672
39-42 warehouses	40 940
43-48 fishery- and agricultural buildings	513 623
49-57 office and commercial buildings	38 772
58-67 communication and transport buildings	10 272
68-79 hotel and restaurant buildings	31 270
80-89 educational buildings	18 640
90-93 + 100-103 other cultural buildings	12 248
94-99 sport/athletic buildings	8 210
104-109 buildings for religios activities	7 228
110-117 hospitals and other health buildings	5 546
118-126 prison, emergency- and other preparedness buildings etc.	4 791
Total buildings stock Norway	**3 932 250**

The largest share of buildings are those categorized as small houses (primarily domestic), detached and semi-detached domestic buildings, single-unit dwellings with lodgings/ bed-sitting rooms or basement apartments, farmhouses, variations of vertically or horizontally semi-detached houses, townhouses, chain- and atrium houses, terrace houses and other types of small houses with three or more dwellings. The large number of smaller buildings in the categories 1-30 gives an explanation to the large total number of buildings (Table 1). For comparison, the Norwegian population is 4.99 million per 1. February 2012.

Access and climatic conditions have at all times been two of the main factors in choosing building materials. Due to easy accessible timber in most of the country, wood has traditionally been preferred. Norwegian architectural style is still characterized by wood as the prevailing building material, also in modern architecture, except in the most urban areas. The use of wood displayed in facades together with glass, steel, and concrete elements is in fact also trendy in built-up, down town areas and multi-storey buildings. The use of wood as the main material applies in particular to dwellings, small garages, sheds, cabin/second homes and fishery- and agricultural buildings. Presently, 75 – 80 % of all newly contructed dwellings are wooden (frame houses). In the category *small houses* the share of wooden houses is exceeding 98 %. Smaller, one to two storey service buildings are also most frequently wooden. Timber framework is most common also when it comes to supplementary, non-loadbearing walls and inner partition walls in buildings with concrete substructures (Edvardsen & Ramstad, 2006). It is assumed that the concentration of concrete, brick and masonry, and steel buildings is much higher in urban areas with the highest concentrations of the population.

The housing stock of Norway is to a large extent private property. Nearly 80 % of Norwegian households own their dwelling. This constitutes 1.84 million dwellings, of which 1.2 million are single-unit dwellings. In addition, the major part of the 1.2 million garages, sheds, temporary dwellings etc. linked to dwellings and cottages are also in private ownership. It is reasonable to assume that the nearly 482 000 buildings employed as holiday cottages/second homes are also privately owned. Thereby, quite a large share of the Norwegian building stock is managed and owned by non-professional owners, responsible for maintenance in general and i.a. climate adaptation of their properties. The owners of the remaining building stock are more or less professional; co-operative building societies, public and private professional owners, municipalities etc.

2.3 Climate challenges

The climate of Norway is extremely varied. A rugged topography induces large local differences in temperatures, precipitation and wind velocities over short distances. Seasonal variations are also extreme. A long coastline and steep topography make it particularly vulnerable to frequent and extreme events such as coastal storms, avalanches and landslides. From the southernmost point to the northernmost extremity there is a span of 13 degrees of latitude. Figure 1 displays Norwegian climate according to the Köppen climate classification system.

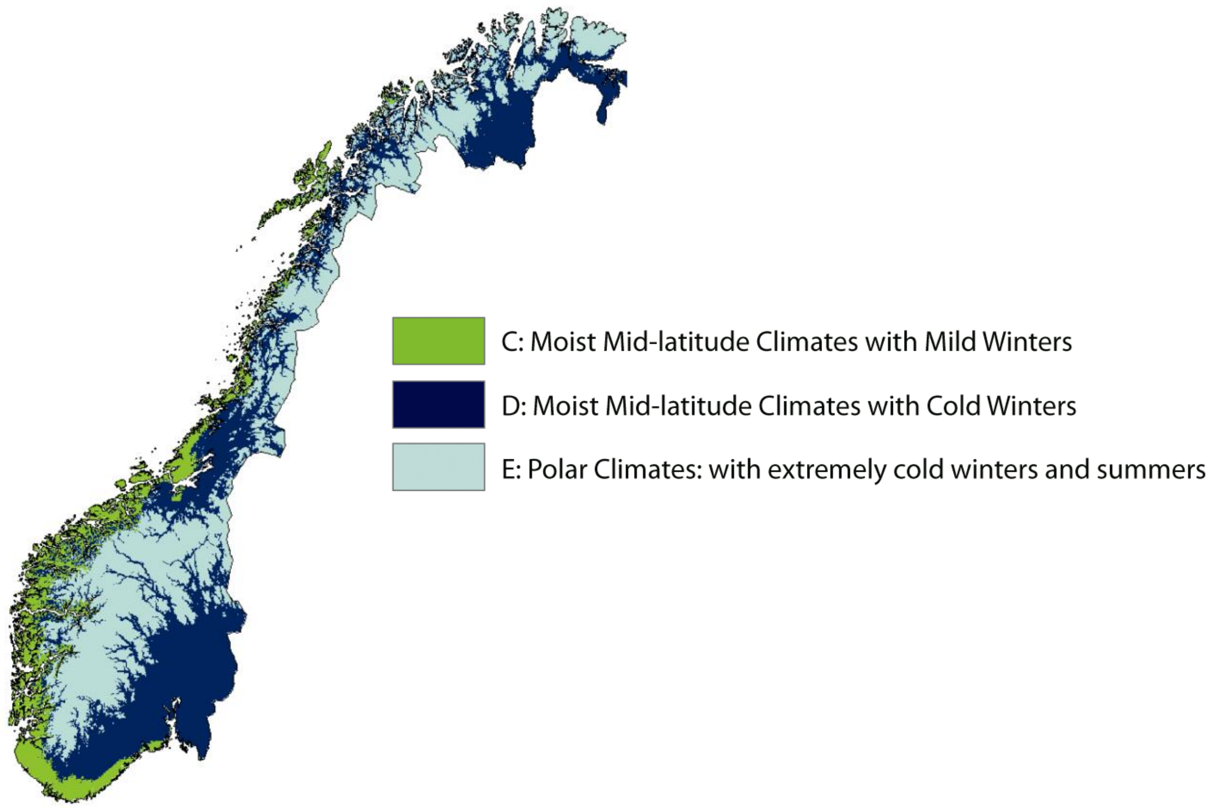

FIGURE 1: The climate of Norway based on the Köppen Climate Classification System. The map is prepared by the Norwegian Meteorological Institute, using weather data (annual and monthly averages of temperature and precipitation) from the reference 30-year period 1961–1990 (Lisø 2006).

Köppen Climate Classification System is one of the best known and most utilized climate classification systems. It was developed by Wladimir Peter Köppen around 1900, and later modified. The system combines annual and monthly temperature and precipitation normals. The Köppen System is originally divided into five main climate zones, again divided into additional climate types and sub-types. Applied to Norway, three main climate zones are displayed; moist mid-latitude climates with mild winters, moist mid-latitude climates woth cold winters and polar climates with extremely cold winters and summers.

The long coastline of Norway is facing the northern extension of the Gulf Stream. This induces a much milder climate than indicated by the latitude. The highest annual temperatures are found in coastal areas of the southern and western part of the country. The coldest area is situated at the Finnmark Plateau in the inlands of the north (when excluding uninhabited mountain areas). The large weather systems mainly come from the west. The normal annual precipitation in Norway is also subject to vast local and regional differences. Among the highest in Europe, the largest normal annual amount of precipitation comes to more than 3500 mm, some miles off the coast of Western Norway. Low annual precipitation with showery precipitation during summer as the main contributor is common for the inner parts of Eastern Norway, the Finnmark Plateau, and some smaller areas near the Swedish border.

2.4 Climate change and future climate scenarios for Norway

The final report from the program Climate 2000 (Lisø and Kvande, 2007) concludes that the vulnerability of the built environment and other infrastructure will be enhanced by climate change. In general, future constructions in parts of the country will meet increased external climate strain, mostly related to moisture. The built environment has an expected lifetime of 60 to 100 years. Increasing and changing climate strain must be an immediate consideration, in order to maintain these expectancies, develop a sustainable new built environment, and to ensure the least possible negative effects to the environment. Improved methods are necessary to assess risks of climate change, in order to implement effective measures for climate adaptation.

Climate change will cause more extreme weather events, increasing the challenges for the built environment. To some extent, risks of extreme weather events should be employed as design loads in structural design and localization of buildings. This may be in case of e.g. extreme wind loads in exposed areas, storm surges and flooding, and high intensity precipitation in vulnerable catchment areas with confined natural run-off possibilities.

Claims payment by insurance companies due to extreme weather events are however marginal compared to the extent of the costs of annual building defects in Norway. Analyses of the SINTEF Building and Infrastructure Building Defects Archives (Lisø et al., 2006) substantiate that the principal engagement should still be to reduce the quantity and severity of moisture defects, also when facing a changing climate. As an example, the combination of increased precipitation and temperatures will increase the risk of undesirable biological growth in constructions all over the country. The primary areas to be hit by extreme weather events are situated along the coastline from south-west (Rogaland) to north-east (Finnmark) of Norway.

2.5 Brief overview of building defect situation in Norway

Climate challenges have always required major considerations in building design and construction. Due to vast geographical changes, even within very short distances, building tradition has developed with distinctive, locally contextual characteristics, with evident differences in design dependent on localization and local climate loads. Due to i.a. industrialization of the building process, changes in trends and a general economical and technical development, such variations are no longer as locally dependent as before. The use of new materials and rapidly developing technical skills and competence has led to constantly changes of methods of construction and standardization of building design. Yet findings in the Climate 2000 program at SINTEF Building and Infrastructure display (Lisø and Kvande, 2007, and Eriksen et al., 2007) that local climate variations still claim geographically differentiated design and knowledge of local climate conditions in order to maintain a built environment well adapted to local climate challenges.

The amount of process related building defects is however far higher than desirable. Increasing demands in the construction industry for profit and shorter construction periods, combined with extremely varied climatic impacts during the construction process, enhance the strain in the construction process (Lisø et al., 2003; Lisø et al., 2006). In order to further develop existing design tools and facilities, solutions, and preventive measures to obtain functional building envelops, building defects analyses are necessary. As part of the comprehensive analysis of empirical data gathered in a fifty-year period on process related building defects, the vulnerability of different materials and construction details under changing climate exposure has been investigated (Lisø et al., 2006). The electronic building defects archive of SINTEF Building and Infrastructure indicate that:

- 3/4 of the investigated defects are caused by moisture;
- 2/3 of the investigated defects are related to the buildings envelope;
- 1/4 of the investigated defects are caused by precipitation;
- 1/3 of the investigated defects linked to outer walls above terrain are caused by moisture;
- 1/2 of the investigated defects linked to roofs and terraces are caused by moisture.

The building defects archive is being pursued and implemented in the *National data base for building quality*. A systematic focus on reduction of building defects through emphasizing on dissemination of knowledge and transfer of experiences may lead to enormous socio-economic expenditure cuts. Further, there is a clear need for information transfer internally within builders' enterprises, pre-fab housing organizations and contractor companies in order to formalize and strengthen local knowledge and learn from the wide range of building defect examples.

3 QUANTITATIVE ANALYSIS – PRESENTATION OF FINDINGS

3.1 Rot decay risk

As increased precipitation and a warmer climate are established impacts in Norway of climate change, the built environment will be increasingly vulnerable to rot decay. The large current amount of wooden buildings and a high number of building defects indicates that future new and refurbished buildings need to be built more robust in order to meet future impacts of climate change (Øyen et al., 2010). In this paper, rot decay risk is defined as risk of rot decay in wooden built constructions above ground.

The rot decay risk analysis (see Figure 2) is based on Scheffer (1971), who developed a climate index for the relative potential for decomposition of wooden constructions above ground in USA. The Scheffer index offers a method to determine the level of rot decay hazard/risk in above ground wooden structures. The formula consists of one factor for temperature and one for moisture:

$$\textit{Scheffer index} = \frac{\sum_{Jan.}^{Dec.}(T_{mean}-2)(D-3)}{16.7}$$

T_{mean} is the mean monthly temperature (ºC). D is the average number of days in the month with a precipitation equal to or higher than 25.4 mm (1 inch). The product is summed for all months of the year, and divided with the factor 16.7 in order for the index to be between 0 and 100 for USA. The denominator would be approximately 10 for Norway, based on values for Norwegian metering stations. To enable relative comparison, Scheffers formula has not been changed when developing the Norwegian maps (Lisø et al., 2006).

Areas with potentially high risks of rot decay are substantially expanded in the future (red area in Figure 2). The expansion covers i.a. several of the larger cities with suburbs, with high numbers of buildings.

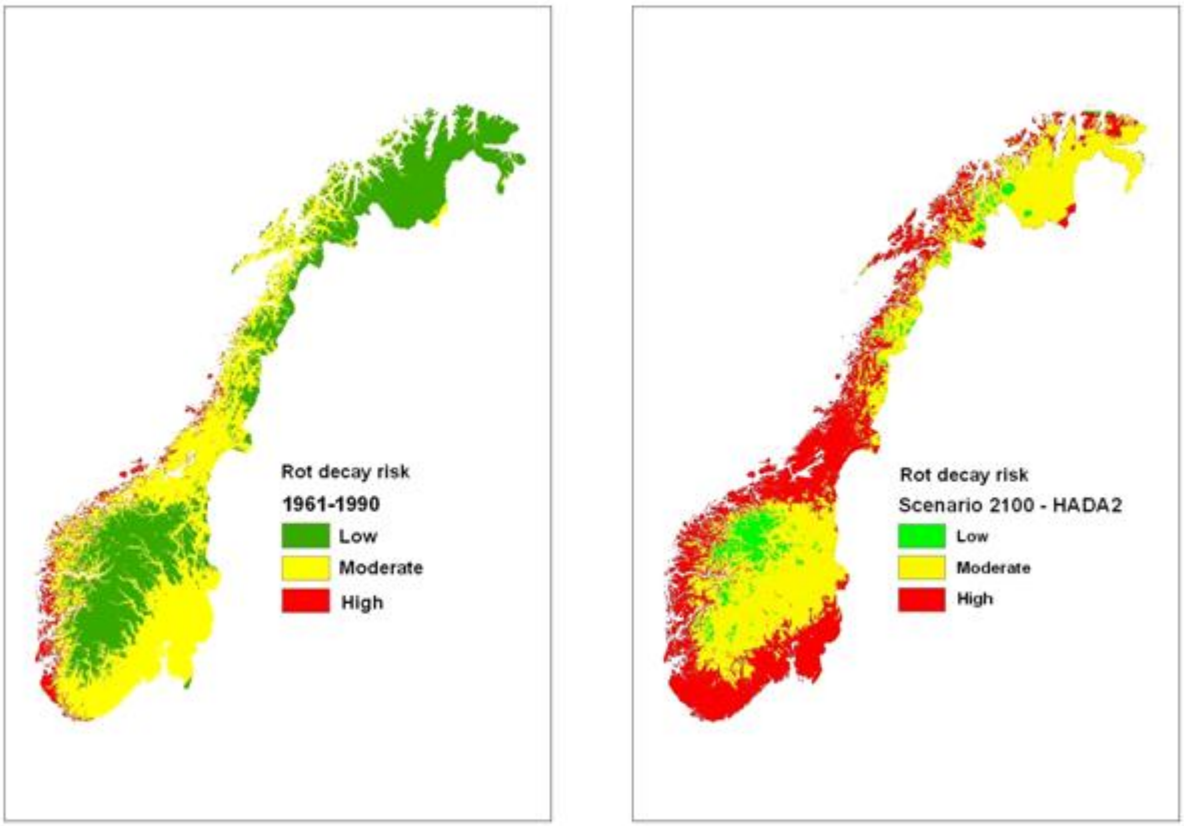

FIGURE 2: Potential rot decay risk map of Norway, presently to the left (based on the normal period of 1961 - 1990) and for the year 2100 to the right. Large parts of the country will be situated in high risk areas in the future, according to a HAD-A2 scenario (based on Scheffer, 1971, Lisø et al., 2006 and Øyen et al., 2010).

Some of the project findings related to rot decay risk:

- Presently approximately 615 000 buildings are located in areas classified as "high" rot decay risk areas;
- In the year 2100, a total of 2.4 million of the present building stock located in areas classified as "high" rot decay risk areas;
- Almost all buildings in Oslo county (south east) will in 2100 be located in areas transformed from "medium" to "high" rot decay classified areas;
- Approximately 190 000 buildings (more than half) of the building stock in Hordaland

county in the West coast, are today located in areas of potentially high rot decay risk;
- In the year 2100, about 220 000 buildings of the present building stock in Hordaland county will be situated in "high" rot decay risk areas.

These are rather dramatic figures, bearing in mind the fact that moisture related building defects presently constitute a very high share of the total number of building defects.

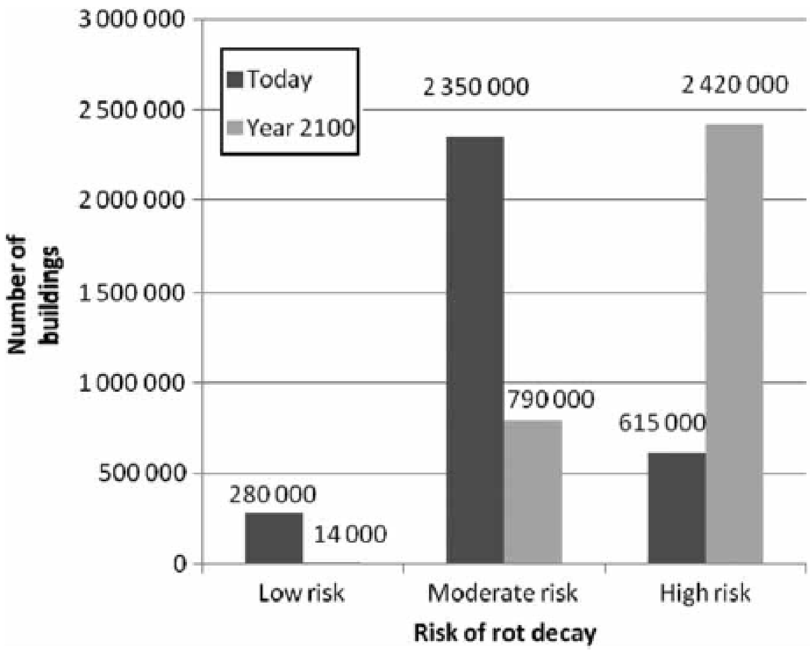

FIGURE 3: Total number of buildings for the mainland of Norway, displaying the different rot decay risk zones for present normal period (1969 – 1990) and for year 2100. The numbers are only accountable for presently existing buildings, as estimates for future buildings towards 2100 are not carried out (Almås et al., 2011)

Figure 3 demonstrates a huge increase of buildings located in high rot decay risk areas in the decades to come. Presently, approximately 615,000 buildings are situated in such areas in Norway. All new buildings will come in addition to this. At this, the main trend of rot decay risk indicates that the main mass of the Norwegian building stock will be situated in high risk areas, as opposed to the present location in moderate risk areas. The scenario maps for rot decay risk in 2100 display that climate change will transform most of the larger cities of Norway to high rot decay risk areas.

3.2 Annual mean temperature

Main trends towards year 2100 indicate an increase of the annual mean temperature, implicating a reduction of the number of heating degree days for most buildings in Norway. These two parameters are of vital importance to the thermal loss of a building.

Temparature changes will lead to a reduction of energy demand in terms of room heating during the cold season. The energy demand for cooling during the warm season will probably also increase, this has however not been subjected in this paper.

- Approximately 2.5 million buildings may meet an increase in annual mean temperature of about 3.4 degrees.

3.3 Snow loads and wet winter precipitation

- The amount of wet winter precipitation will increase in the future. This will potentially entail large consequences, especially in areas where snow loads are presently large. Around 600 000 buildings are in risk areas, given the assessed climate scenario;
- Buildings in both Oppland and Hedmark counties are especially exposed (central sout-east inland);
- Increased loads of snow due to heavier snow, increased quantities of dammed water and higher risks of moisture penetration in buildings are some probable impacts.

3.4 Precipitation

Precipitation loads are presumed increased for all parts of the country, but large local and regional differences are likely to appear. A combined increase of precipitation and wind speed in some areas will increase the strain of wind-driven rain to the buidling envelope. Precipitation is found to be the prevailing cause of building defects in Norway, both alone and in combination with i.a. wind and temperature. A harsher climate with increased amounts of precipitation implies increased strain to the built environment. In this paper, we have focused on precipitation in combination with other climate parameters.

3.5 Frost

- Around 30 000 buildings in Finnmark county (northernmost county on the mainland) will endure even more harsh frost decay strain in the future, while for the rest of the country this strain will most likely diminish;
- Most of the larger cities will be classified as low frost decay areas. Presently, a large number of brick/masonry and concrete buildings are situated in areas classified as moderate or high frost decay risk areas;
- Approximately 900 000 buildings, spread over the country, are likely to have a particularly large drop in amounts of frost decay risk;
- In addition to a reduction of thermal loss, frost insulation of foundations may be reduced;
- Permafrost may diminish and mostly disappear on the mainland, affecting approximately 6 700 buildings;
- Permafrost will most likely be influenced at Spitsbergen, but not grave enough to affect the foundation of the existing 1000 buildings at risk towards year 2100. An analysis and evaluation of foundations in existing building stock is however recommended.

3.6 Sea level rise and flooding

All buildings below one meter above present sea level are situated in risk areas of sea level rise due to future climate change, with the prospects of serious consequences. The production of key figures is in progress but not yet available. Increased amounts of precipitation and more frequent extreme precipitation will increase the challenges in the handling of storm and flood water. Measures directed towards flood related defects by rivers and smaller streams are necessary, however more thorough analyses are requisite.

4 DISCUSSION, CONCLUDING REMARKS AND FURTHER WORK

4.1 Discussion and concluding remarks

The main challenge is not necessarily the changing or aggravating climate conditions, but rather the fact that local climate is not adequately addressed in design and construction of present building projects. Public requirements directed towards municipal authorities regarding the accomplishment of risk and vulnerability analyses (RVA), is a measure of high importance. The latest amendment to the planning and building legislation will probably have a large impact in local planning, regulation, and handling of building applications. This demands resources, competence and access to climate related information on both a municipal and stakeholder level, in order for the local authorities and professional participants of the building process to take actions. The execution of risk and vulnerability analyses will enable the local authorities to be far more forward-looking than what is presently the case.

At the same time, the professional participants of the building process will be introduced to a far better tool for climate adaptive localization of buildings, planning and design. An improved focus on climate adaptation through developing and implementing municipal RVA's, guidelines, as focus in municipal planning and building process etc., will give the work with climate adaptation and strengthening of vulnerability in the built environment the necessary boost. A strengthened political focus on climate adaptation issues for development of the built environment at superior levels of public authorities, will give an important signal both to executive local planning and building authorities, and to professional participants of the building process.

The development and implementation of climate adaptation as an individual discipline, together with a strengthened focus on *climate design of buildings* is requisite in the construction industry and sector at present. In Norway, climate strain during the construction process is a constant challenge on-site. Every year, precipitation causes building defects, both in new construction and refurbishment projects. Measures for moisture proof construction processes will undoubtedly result in a reduction of process induced building defects. The need for competence on building physics, building defects and climate adaptation is steadily increasing. Strickter requirements for documentation of materials tested and approved for different climate strain is higly in demand. Municipal planning, local and development plans and directions for construction and refurbishment/retrofit projects must comprise present climate and future climate scenarios.

4.2 Recommendations for further work

As of July 2010, it is a legal requirement that all Norwegian municipalities work out risk and vulnerability analyses (RVA). This work is however far from being completed, or as for several municipalities, even initialized. All climate parameters mentioned in the basic report of this paper should be addressed in such analyses. In addition, the climate data available, presently and in neer future, should be employed in planning, design and construction of new buildings and building maintenance.

The findings clearly indicate that the climate strain to the built environment will be intensified. This implies stronger requirements and demands in terms of design, planning, construction site logistics and planning of construction site performance both when it comes to new buildings and retrofit/refurbishment projects. Moisture safe building processes and covering of constructions during the construction process will be even more important in the future. Climate change brings along challenges existing buildings are not designed for, and coupled will the present situation of a high quantity of building defects it seems evident that future requirements must demand a far more robust building style, involving i.a. geographically differentiated design. Local climate challenges and large variations of climate strain must be considered, even within short spatial distances. Further development of geographically differentiated design solutions and methods is therefore imperative.

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