Robustness Classification of Materials, Assemblies and Buildings

Bjørn Petter Jelle [ab]*, Erland Sveipe [b], Erlend Wegger [b], Arild Gustavsen [c],
Steinar Grynning [a], Jan Vincent Thue [b], Berit Time [a] and Kim Robert Lisø [d]

[a] Department of Materials and Structures,
SINTEF Building and Infrastructure, NO-7465 Trondheim, Norway.

[b] Department of Civil and Transport Engineering,
Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim, Norway.

[c] Department of Architectural Design, History and Technology,
Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim, Norway.

[d] Department of Knowledge Systems and Certification,
SINTEF Building and Infrastructure, NO-0314 Oslo, Norway.

* Corresponding author: bjorn.petter.jelle@sintef.no (e-mail), 47-73-593377 (phone), 47-73-593380 (fax)

ABSTRACT

Reliable methods are needed for classifying the robustness of buildings and building materials for many reasons, including ensuring that constructions can withstand the climate conditions resulting from global warming, which might be more severe than was assumed in an existing building's design. Evaluating the robustness of buildings is also important for reducing process-induced building defects. We describe and demonstrate a flexible framework for classifying the robustness of building materials, building assemblies, and whole buildings that incorporates climate and service life considerations.

Key words: *Robust, Robustness, Robustness class, Robustness evaluation, Building materials, Building assembly, Building, Climate, Climate class, Climate index, Service life, Service life class, Classification.*

CONTENT

1 INTRODUCTION

The building sector consumes about 40 % of all energy used and waste produced in industrialized countries. One of the sector's greatest challenges is to reduce this energy use and waste stream. Using robust building materials and components helps to reduce building-sector waste by minimizing the need for renovation or replacement during a building's construction and operation. Building envelopes need fulfill a number of functions including providing load bearing, thermal insulation, and a comfortable indoor environment. In addition, buildings should be durable and built to minimize defects and the quantity of materials used. Characterizing the robustness of today's buildings and their components parts will help us develop tomorrow's more robust solutions.

This work attempts to define the term "robust" accurately and propose a framework for classifying the robustness of building materials, assemblies of materials used as components in buildings, and whole buildings. Beneficiaries of this robustness classification framework will be all the various value segments within the building sector, e.g. planners, designers, material suppliers, contractors, clients, house owners, etc.

Resilience and durability are important properties that make a material or solution robust. In the proposed framework, robustness is determined at the three levels of detail identified above: materials, assemblies, and whole buildings. The robustness classification also incorporates classifications of climate and service life. That is, the climate and service life and their variabilities are integrated within the robustness classification framework. Furthermore, weight factors are applied to customize the evaluation for different conditions and locations. We illustrate the robustness classification method using several examples of materials, assemblies, and whole buildings: a vacuum insulation panel (VIP), a nano insulation material (NIM), mineral wool, concrete, VIP within a sandwich element, a window, a typical Norwegian timber frame building, and the Pyramid of Cheops. The proposed framework is designed so that it can be flexibly refined.

2 ROBUSTNESS

Classifying buildings and their components according to their robustness requires that we first define the term "robust." Robustness could encompass a wide range of properties or aspects, the choice of which will affect the outcome of the evaluation. An extremely broad definition could, for example, include a building's political or economic robustness. However, we seek a concise definition of robustness to evaluate the durability and resilience of a building and its components. The dictionary definition of robustness includes terms such as "strong," "tough," "powerful," "hardy," "rugged," "sturdy," "resilient," "strong in form," and "sturdily built." However, robustness refers to more than mechanical properties. For our classification system, we use the robustness definition from the SINTEF and NTNU project "Robust Envelope Construction Details for Buildings of the 21st Century" (ROBUST): *"materials and solutions having a high resistance against failure (e.g., moisture problems), and having a high probability of being constructed according to specifications. The service life of the materials and solutions will also be important*."

Robust materials and solutions are meant to have: a high resistance to mechanical failure, including damage from climate load; and design properties that facilitate simple and durable solutions, which relates both to the production and operational phase of the building or its components. For a whole building, robustness includes elements beyond the actual materials of the building, e.g. energy robustness. The robustness of a building and its parts is also relative to the climate to which they are exposed as well as to their intended service life. We propose a number of aspects for evaluating the robustness of a building and its components.

2.1 Robustness for different levels of detail of a building

Different materials and parts of a building may exhibit different degrees robustness but the building as a whole may still be regarded as robust. A building can be subdivided into component parts in different ways. For the robustness framework, we evaluate the whole building as well as two different levels of detail within the building: building materials and building assemblies.

In this robustness classification system, *materials* refers to building materials or heterogeneous or homogenous combinations of materials (both alloyed and non-alloyed) as well as to two or more separate materials put together that function like a building material, e.g., a vacuum insulation panel (VIP). A building *assembly* refers to a section of a building envelope that is made up of several materials and components. An example is a window or a joint between a wall and the roof. The most general level of evaluation is the *whole building*. Determining the robustness of the whole building might be regarded as an ultimate goal of this research. Thus, the robustness categories we evaluate are: robust material (RM), robust assembly (RA), and robust whole building (RB).

2.1.1 Robust building materials

We can divide the life of a building material into three phases: production, operation, and disposal. Robust properties are important even in the disposal phase when materials may be reused and recycled. Table 1 shows the different life stages of building materials. There are equivalent stages for building assemblies and whole buildings that are not depicted in this table.

Table 1. Stages in a building material's lifetime.

Production phase				Operational phase (service life)	Disposal phase	
Production	Transport	Storage	Implementation, Construction	Use Wear and tear, extraordinary and catastrophic loads, etc.	Demolition Reuse, Recycling	Depositing, Disposal
Climate exposure						
Environmental impact over lifetime						

Table 1 indicates the complexity of the robustness evaluation. A material must be robust in different settings from the production phase to the disposal phase as well as in relation to climate and environmental impacts over the material's lifetime. Aesthetic properties are not part of the definition of robustness for this research, but aesthetic aspects could be considered as part of the evaluation of durability.

2.1.2 Robust building assembly

A robust building assembly consists of robust materials and is easy to build. Thus, in addition to meet the same robustness aspects or criteria that apply to building materials, an assembly must meet a design quality standard that gives a high probability that the assembly will be built as designed or will function effectively if construction deviates from the design intention. When different materials are combined in an assembly, they must be robust in interaction with one another; for example, two different metals in contact could induce galvanic corrosion, which would compromise an assembly's robustness. Use of robust building assemblies should reduce the amount and frequency of building defects and therefore result in less material used during construction and operation. Thus, a robust assembly will be economically profitable and environmentally beneficial as long as the materials from which it is made have low or average environmental impact during their lifetime.

2.1.3 Robust building

In the same way that a robust assembly's materials must maintain their integrity when they interact, the different assemblies in a whole building must remain robust when they interact. This is mainly a design quality issue. The building must be easily built as designed, and the materials in the building must be put together in a reasonable way. Whole-building robustness encompasses a larger perspective than does robustness of a material or assembly. For example, it is recommended that a building will be energy robust, e.g., highly energy efficient, with high-performance thermal insulation and the ability to utilize different sources of energy. In addition, it is advantageous if the building design is robust in the sense that the building can be used for different purposes and is easy to remodel. It may also be important for a robust building to have components or groups of related components with comparable lifetimes; for example, the less accessible components of a wall should normally have a longer lifetime than the outer, more accessible parts of the wall.

2.2 Robustness in relation to climate, service life and use

To assess the impact of climate and service life on a building's robustness, we use the following definitions (ISO 6707-1:2004, ISO 15686-1:2000):

- Durability – Capability of performing required functions over a specified period of time while subject to the conditions anticipated during service
- Service life – Period of time after installation during which a building or its parts meet or exceed performance requirement(s)

Service life is a time span specified in years, and durability is a property of the building or its parts that results in a specific service life (Brischke 2006). For purposes of robustness classification, durability is an important aspect that primarily evaluates resistance to climate impacts. Thus, the robustness of a building and its parts is relative to different conditions, and climate and service life have a major impact on robustness.

When we address climate, we generally consider the relevant microclimate because it has the greatest impact on the building's durability (Haagenrud 1997) and therefore the robustness of the specific material or building being evaluated. In some climates most materials may be robust; for example, in a dry climate many materials are very durable. Other climates are so severe that most materials decay quickly. Different materials respond differently in different climates. Currently, climate is characterized in the framework using selected climate factors, e.g., measurements of wind-driven rain. In the future, we envision using *climate classes* that characterize a climate using a single number. This would make it easier to classify the robustness of different building elements with respect to different climates. In this work we use a system of climate classes for the robustness evaluation.

The indoor climate of a building has a significant influence on the building's durability and thus its robustness. Indoor climate varies substantially with the type of building (residential, industrial, medical, etc.). Nonetheless, a mean indoor climate value may be assumed based on the climate at the building's location and the nature of the building's use. The framework we present for classifying robustness makes it possible to take the building's use and indoor climate into account within proposed evaluation categories (e.g., climate and physical evaluation of the building). Because buildings vary widely in their uses as well as the craftsmanship of their materials, we focus on evaluating the robustness of general types. For example, when we evaluate a certain type of building assembly, we assume an average good implementation of the assembly and a normal building usage.

Based on the explanations above, robustness may be defined as a building's *ability to perform its function during its service life in a specific climate*. Thus, in a specific climate, a building and its parts may have different robustness because of differences in service life. For some materials or assemblies, for example, the intended service life may be less than a year, and, for others, it may be several hundred years. That is, in this context a material may be less robust if the requested service life is prolonged.

3 CLIMATE LOAD

The lifetime of the built environment depends heavily on the severity of local climate conditions, and climate and topography put great demands on the design and location of buildings (Lisø 2006a). Methods and approaches to assess climate change risks are necessary to develop design guidelines for a robust built environment.

Moisture problems account for 76 % of all process-induced defects in building enclosures in Norway, and 24 % of these problems are directly caused by precipitation (Lisø et al. 2005). Water is one of several climate factors. Based on these statistics regarding the impact of water alone, it is evident that evaluations of a building's robustness to different climate factors are of great importance. Table 2 shows an overview of different climate factors (based on Jelle et al. 2008, Jelle et al. 2012, Jelle 2012a), which we use to evaluate the robustness of buildings and their components to climate conditions. The information in Table 2 is also the basis for the climate index we developed for the robustness framework, which is described later in this report.

Table 2 lists nine climate factors, weighted according to importance. Some important factors are subdivided, for example, "temperature" and "temperature cycles" or "air humidity" and "water". Others are listed as a single factor; for example, "erosion and corrosion" is treated as a single factor. Oxygen availability and time are not considered climate factors for purposes of this evaluation because evaluations of all factors are relative to time in the framework; that is, we use service life as the basic time measurement in our robustness evaluation. Oxygen is considered to be available at all times.

The weight factors in Table 2 allow differentiation of the relative importance of the climate factors, which varies according to the material or component considered. For example, resistance to solar radiation is of less importance for a built-in thermal insulation material than for a wall cladding. These weight factors are applied for both the climate classification and robustness classification at all three levels of detail for a building. The choice and weighting of factors have a large influence on the final robustness and are further elaborated in Section 4.5. The term "total climate load" includes all the relevant climate factors listed in Table 2.

Table 2. An overview of climate factors to which materials, assemblies, and buildings may be exposed (based on Jelle et al. 2008, Jelle et al. 2012 Jelle 2012a). The total climate load includes all the relevant climate factors.

	Climate factors	Weight factor (0-100)
Climate factors are used to address the durability of materials, assemblies, and buildings, and are also used separately to classify local climates.	**CF1:** Solar and thermal infrared radiation **CF2:** Temperature (high/low) **CF3:** Temperature cycles (e.g., freeze-thaw cycles) **CF4:** Air humidity **CF5:** Water (e.g., wind-driven rain) **CF6:** Wind and air pressure **CF7:** Erosion and corrosion **CF8:** Pollution including micro-organisms **CF9:** Synergy and oscillation between conditions	**CF1:** 80 **CF2:** 70 **CF3:** 60 **CF4:** 100 **CF5:** 100 **CF6:** 20 **CF7:** 40 **CF8:** 50 **CF9:** 40

To describe each climate factor in detail falls outside the scope of this work, but the following issues should be noted:

Solar radiation may cause decay of materials, for example due to photodegradation processes in which UV radiation and short-wave visible light play a significant role. Evaluating temperature tolerance includes consideration of high temperatures, low temperatures, and differences in temperature on a building or building component. Materials often change mechanical properties with temperature, for example becoming more brittle when cooled down. The kinetic reaction rate of chemical processes increases exponentially with increasing temperature. The decay potential in wood structures in Norway based on Scheffer's index was presented by Lisø et al. (2006b). Decay potential is related to three climate factors: temperature, water, and synergy among conditions.

The evaluation of the impacts of temperature cycles on a building and its parts includes both thermal expansion/contraction and freeze-thaw cycles. A frost decay index for porous, mineral building materials was developed by Lisø et al. (2007). This index takes into consideration both the presence of water and the number of times that the temperature drops below 0°C. Differences between humidity levels in materials and in the air, or between various materials, will strive to equalize these humidity concentrations. High relative humidity may be disadvantageous for some materials; others might not tolerate low relative humidity. The climate factor that labeled as "water" in Table 2 includes precipitation, wind-driven rain, and scouring. A driving rain index that may be used in evaluations of robustness to water was presented by Rydock et al. (2005).

If a building is not correctly designed or constructed, wind may cause damage. Air pressure differences between outdoors and indoors may be critical in some cases, including the potential for radon to penetrate from the ground into a building via air leakage and diffusion (Jelle et al. 2011, Jelle 2012b). The Norwegian standard for wind design loads (NS 3491-4) uses a factor describing reference wind speed at sea level at different locations. Evaluation of erosion tolerance includes all types of degradation from climate loads and corrosion processes, where e.g. galvanic corrosion among different materials is part of this climate factor. Evaluation of robustness to pollution addresses the effects of various chemicals, micro-organisms, and bacteria.

Finally, after evaluating a building or component's resistance to each individual climate factor, it is important to consider miscellaneous synergies that might amplify the climate stresses. Effects from oscillations between different conditions, e.g., between a humid and dry climate, should also be considered if not already accounted for in the above-mentioned climate factors.

4 ROBUSTNESS CLASSIFICATION

Europe has labeled energy-efficient electrical equipment and household appliances for some years and has now introduced in the building sector as well. Starting in 2010, all new buildings in Norway must have an energy label (Harket 2009). Energy labeling is not sufficient to achieve the 21st century goals related to building energy efficiency, indoor climate, environmental impact and minimization of building defects. Use of robust materials and building solutions is important to minimize defects during both construction and operation of buildings and allows for a longer service life of materials and buildings. The gain is reduced costs from building defects, reduced use of materials, and a reduced environmental impact. Ultimately, it must be determined at what level the robustness classification should be carried out, and under whose authority (for example, robustness could be incorporated into building codes).

4.1 General method

The proposed method for classifying the robustness of materials, assemblies, and buildings entails the following steps:

- Determine evaluation aspects (criteria) for a given climate and service life
- Normalize the sum of the weighted ratings of the aspects
- Determine the robustness class

Table 3 shows an example of a robustness classification. Table 4, Table 5, and Table 6 show a number of *evaluation aspects* for the three levels of detail of a building, i.e., building materials, building assemblies, and whole buildings. These aspects take into account robustness during both the construction and operational phases of a building's life. Each of the aspects evaluated for a given level of detail is rated from 100 (excellent) to 0 (too poor), as shown in Table 7. This evaluation is a quantitative judgment, and the ratings may be either absolute (i.e., independent of increase or change in the quality of the particular building or material over time) or relative to the standard of today's materials, assemblies, and buildings. The rating is also highly dependent on the climate in which the building will be located and how long the building is expected to operate. Table 8 and Table 11 present the *climate class* and *service life class*, respectively. The different evaluation aspects are given different weight factors (0-100), based on the probability and consequences of failure. The products of *aspects ratings* and *weight factors* are summed and normalized as a ratio, which gives the *robustness value* as follows:

$$\text{Robustness value} = \frac{\sum_{\text{i}} \{(\text{Aspect rating})_{\text{i}} \cdot (\text{Weight factor})_{\text{i}}\}}{\sum_{\text{i}} \{(\text{Weight factor})_{\text{i}}\}} \qquad (1)$$

Note that the proposed elements to be evaluated comprise various aspects and weight factors. In addition, the weight factors may change according to the importance of different aspects in different regions, hence the proposed system has built-in flexibility. The calculated robustness value corresponds to a given *robustness class* that ranges from "A" (best) to "G" (weakest). Table 3 shows the relationship between the robustness value and the robustness class. The actual values used here for evaluation aspects and weight factors represent proposed values and will be subject to change.

4.2 Robustness classes

The proposed classification shown in Table 3 uses the same eight classes and colours as the European energy label system recently taken into use. In addition, three overarching categories, i.e. robust, less robust, and not robust, have been defined. The robustness value is defined as a normalized sum of the weighted ratings, as shown later, and is influenced by climate and service life.

Table 3. Robustness classification with robustness classes "A" (best) to "G" (weakest) and corresponding robustness values (100-0).

	Robust			Less Robust		Not Robust	
Robustness class	**A**	**B**	**C**	**D**	**E**	**F**	**G**
Robustness value	[100-90]	<90-80]	<80-70]	<70-60]	<60-50]	<50-40]	<40-0]

It is important to state the climate class and service life class on which the robustness class was based on (determined from) because robustness varies strongly according to these two parameters; for example, for a short service life most materials are robust.

4.3 Evaluation aspects

Several different aspects have to be considered when evaluating robustness. The three levels of detail into which a building is subdivided for robustness evaluation (materials, assemblies, and whole buildings) require different aspects for evaluation. Proposed evaluation aspects for building materials, building assemblies and whole buildings are presented in Table 4, Table 5 and Table 6, respectively. What aspects to include and what weight each should have may still be subject to change as the robustness framework may develop in the coming years. The evaluation of the aspects has to be carried out with respect to a given climate (climate class) and service life (service life class).

A building assembly consists of several materials, which complicates the robustness evaluation because different materials have different robustness. The placement of materials and their interaction with each other is another crucial aspect to be evaluated and may be affected by the building design. The robustness of the whole building gives an overall assessment. The mechanical loads at the building level (in the operational phase) that are not part of catastrophic loads (RB4), and the durability and climate loads (RB5), are normally covered at the level of materials. Furthermore, energy class and flexibility are proposed to be included as building evaluation aspects.

Table 4. Elements of robustness evaluation, with corresponding weight factors, for building materials.

Level of detail	Materials evaluation aspects	Weight factor (0-100)
Building materials *Aspects that must be evaluated when robustness of materials is classified.* *Class: Robust Materials RM.*	**RM1:** Mechanical loads and various strains **RM2:** Total climate load (Table 2) in the production phase **RM3:** Durability; toleration of total climate load (Table 2) during the operational phase **RM4:** Catastrophic loads **RM5:** Installation/adaptation to the application **RM6:** Range of use and usability **RM7:** Environmental impact over lifetime	**RM:** 60 **RM:** 40 **RM:** 100 **RM:** 30 **RM:** 50 **RM:** 20 **RM:** 70

Table 5. Elements of robustness evaluation, with corresponding weight factors, for building assemblies.

Level of detail	Assembly evaluation aspects	Weight factor (0-100)
Building assembly *Aspects that must be evaluated when robustness of assemblies is classified.* *Class: Robust Assembly RA.*	**Implementation phase** **RA1:** Mechanical loads and various strains **RA2:** Total climate load (Table 2) **RA3:** Catastrophic loads **RA4:** Buildability/implementability **RA5:** Range of use and usability **Operational phase** **RA6:** Mechanical loads and various strains **RA7:** Durability; toleration of total climate load (Table 2) **RA8:** Catastrophic loads **RA9:** Replaceability **RA10:** Material match/interaction **RA11:** Building physical aspects **RA12:** Environmental impact over lifetime	**RA:** 30 **RA:** 30 **RA:** 20 **RA:** 40 **RA:** 40 **RA:** 60 **RA:** 100 **RA:** 60 **RA:** 30 **RA:** 50 **RA:** 10 **RA:** 100

Table 6. Evaluation aspects with corresponding weight factors for whole buildings.

Level of detail	Building evaluation aspects	Weight factor (0-100)
Whole building *Aspects that must be evaluated when robustness of buildings is classified.* *Class: Robust Building RB*	**Construction phase**	
	RB1: Catastrophic loads	**RB:** 30
	RB2: Total climate load (Table 2)	**RB:** 20
	RB3: Buildability	**RB:** 30
	Operational phase	
	RB4: Catastrophic loads	**RB:** 50
	RB5: Durability; toleration of total climate load (Table 2)	**RB:** 100
	RB6: Interaction of different assemblies	**RB:** 20
	RB7: Energy class	**RB:** 80
	RB8: Flexibility, ability to change floor plan and remodel	**RB:** 70
	RB9: Building physical aspects	**RB:** 50
	RB10: Environmental impact over lifetime	**RB:** 50

4.4 Robustness rating of building elements

The robustness of buildings and their parts is determined by rating the elements listed in Tables 4 – 6 given above. Table 7 shows the framework for quantitative ratings. The *building aspects evaluation* gives corresponding adjectives to help rate the robustness of building elements on a scale from 0 to 100. The rating may be absolute or relative to the standard of today's materials, assemblies, and buildings. If the rating is relative, materials and solutions may need to be reclassified as the standard of quality develops over time; for example, *excellent* properties today may only be rated as *good* in 50 years as a result of advances in design, technology, etc. Section 4.6 describes the basis for this evaluation. It is important to keep the definition of robustness in mind as the basis for ratings. For example, when rating a building material, it is necessary to differentiate between robust properties and other properties such as e.g. economy. When a building element is rated within the two lowest categories (poor or too poor, 0-50), it is not considered robust enough for use in buildings. A poor rating does not automatically place a material or component in robustness class "G," however, because poor properties may be accounted for in a design or building so that the final solution is robust even if a given material or component is not. For instance, concrete may receive a low rating for total climate load in the production phase, nevertheless, in overall the concrete material may be regarded as robust.

Table 7. Rating scheme for building aspects from 0 (too poor) to 100 (excellent). The rating is based on a quantitative evaluation of the element.

	Robust			Less Robust		Not Robust	
Building aspects evaluation	**Excellent**	**Very Good**	**Good**	**Fair**	**Moderate**	**Poor**	**Too poor**
Aspect rating	[100-90]	<90-80]	<80-70]	<70-60]	<60-50]	<50-40]	<40-0]
Robustness class of a single aspect	A	B	C	D	E	F	G

The robustness values given in Table 3 correspond directly to the proposed rating of elements in Table 7, with the difference being that the robustness value considers the normalized sum of ratings, and the building element rating looks at a single element. The rating system has the same number of levels as there are robustness classes, so the rating of each building aspect can be presented using the same colour codes as for the robustness classes, and each aspect can be assigned a *robustness class*.

4.5 Weight factors

In the future, we envision that the weight factors will include both a risk factor and an impact factor, to account for the risk or probability that an incident might occur and the impact or consequence if that incident occurs. A consequence could be related not only to robustness, but could also, for example, involve a safety or health impact. However, we do not elaborate this subdivision of the weight factors into risk and impact in the current framework given here.

The weight factors also account for the relative importance of the particular aspect being evaluated within the total robustness classification. That is, the weighting is not uniform for the three levels of detail of a building or for climate or service life. An example is that the probability of catastrophic loads may be different for different locations; the risk of an earthquake is greater in Los Angeles, California than in Oslo, Norway. Therefore, the weight factor for catastrophic loads must be greater in Los Angeles. These types of adjustments in weight factors make it difficult to compare robustness from one building or location to another. Thus, it might be appropriate for weight factors to be held constant within geographic areas and/or climate zones. Nevertheless, the presented framework for the robustness classification has a built-in flexibility so these issues may easily be implemented, i.e. the framework itself is robust with respect to flexibility.

The choice of weight factors has a significant influence on the calculated robustness, i.e. the relative weightings among aspects have a direct impact on the final robustness value and robustness class. An example is that the influence on the total score of a factor that is weighted at 100 will change depending on the total sum of all of the weight factors. Thus, the various weight factors have to be chosen carefully. Tables 4, 5, and 6 show proposed weight factors for the three levels of building detail. The weighting of the factors in these tables is illustrative because it is outside the scope of this work to determine these weightings precisely. These illustrative weight factors are utilized to demonstrate the robustness classification method in this paper. Table 2 shows the climate load and proposes weight factors for corresponding climate factors. The basis for the climate weight factors is the same as described above for the weight factors for building aspects. That is, the climate weight factors consider the risks, consequences, and relative importance of the specific aspect of climate load. For simplicity, the climate factor weightings are the same for both the evaluation of durability (tolerance to climate loads) for all levels of detail of buildings and for the overall climate classification. These weight factors add to the built-in flexibility and versatility of the robustness classification system.

In certains areas and for specific purposes there exist various methods for determining weight factors either qualitatively or quantitatively, e.g. note the study by Choo et al. (1999) about interpretation of criteria weights in multicriteria decision making and the work by Qureshi and Harrison (2003) with an analytic hierarchy process application example. However, note that the objective of this work is to describe and demonstrate a flexible framework for robustness classification of building materials, building assemblies, and whole buildings. Hence, this work is not about deriving the weight factors. In fact, in many cases the weight factors do not need to be derived according to a systematic method with mathematical correlations. They may be chosen as specific values according to what aspects we or others want to give more or less weight. This is a common practice in several other areas dealing with classifications applying weight factors. One example may be classification of car tires, where evaluation aspects may be braking length on dry asphalt, braking length on wet asphalt, braking length on snow, braking length on ice, stability in curves, noise level, etc. (and e.g. the same properties for aged/used tires), where all of the aspects are given specific weights. From the above it is clear that it does not exist a systematic (mathematical) method for deriving the weight factors, e.g. how should one derive the weight factors systematically according to a specific and general, mathematical method including such fundamentally different properties as e.g. braking length and noise levels? These weight factors are determined through given and specific preferences for comparison reasons, and may also be changed according to what one wants to place emphasis on, i.e. place/give weight on (i.e. the term weight factors). This is also valid for the robustness classification presented in this work. Furthermore, an attempt to make a systematic method with mathematical correlations for deriving the weight factors for the given robustness classification would be an enormous task and probably rather futile in most cases with respect to their intended use. Nevertheless, as mentioned earlier, future weight factors may include risk (probability) and impact (consequence) factors. Thus, as a summary, the weight factors are determined through given and specific preferences for comparison reasons, and they may also be changed according to what aspects or properties one wants to place emphasis on for specific cases. That is, there is, and should or can not be, any systematic and general, mathematical method for deriving all the weight factors in the presented robustness classification.

4.6 Basis for evaluated building elements

Each of the aspects listed in Table 4, Table 5, and Table 6, for building materials, building assemblies, and whole buildings, respectively, may be elaborated further to describe the basis for the required evaluations. This section presents examples to give the reader a sense of the basis used for each aspect. The evaluation for each aspect may be based on national or international standards, regulations, and test methods that apply to the relevant building component.

For example, evaluation of mechanical loads and strains on building materials and solutions (RM1) for the thermal insulation material mineral wool must consider several properties. Mineral wool tolerates nail penetrations without major changes in its properties; the only negative consequence might be the creation of small thermal bridges. Therefore, mineral wool may be considered robust with respect to nail penetrations. However, a uniform distributed load can compress mineral wool so that its thermal insulation resistance is reduced. Mineral wool's thermal insulation resistance may also be decreased by exposure to water or high levels of moisture. Similarly, for each building element, several properties and functional requirements are evaluated.

Different types of building materials can differ significantly in the degree to which they tolerate variations in installation or application (RM5). For example, the materials mineral wool and concrete are highly adaptable to varying applications when installed, but vacuum insulation panels score very low on this aspect. Another example relates to the evaluation aspect "buildability/implementability" for building assemblies (RA4), which considers how well the assembly as built tolerates variations from its original design. For prefabricated elements, this aspect requires evaluation of the probability that the element will be installed correctly. The evaluation process also includes an assessment of how easily an assembly can be built and the need for special precautions in constructing it. A simple and robust assembly is more likely to be built correctly than a complex and robust assembly. Therefore, the simple assembly might result in fewer process-induced building defects. The evaluation aspect for "replaceability" of building assemblies (RA9) might consider, for example, how parts that are particularly exposed especially to wear and tear or damage can be replaced. An assembly might contain parts that not are very robust, but if these parts can be replaced easily, this makes the assembly more robust due to its design. The evaluation aspect "material match/interaction" for building assemblies (RA10) might take into account whether specific materials decay more rapidly in contact with other materials, e.g. galvanic corrosion between different metals. The evaluation aspect "building physical aspects" for building assemblies (RA11) might, when evaluating a building component that is in itself robust, consider that when this component is put together in an assembly, physical issues could make that component vulnerable to moisture problems. Some of these issues within aspects RA10 and RA11 can also be seen as durability questions, but they are identified separately within the evaluation framework because of their importance.

The robustness rating of a building reflects the building as a whole. For example, wear and tear of a floor covering (building material) will normally not be included in the evaluation of the robustness of a whole building. However, if deterioration in a building material results in degradation of the building as a whole, this must be covered by the whole-building evaluation aspects. As an example, if a moisture barrier is not performing according to specifications, which results in moisture damage, this is accounted for by a low rating for aspect RB9, building physical aspects, at the whole-building level of detail. The aspect "buildability" for whole buildings (RB3) might consider that a simple and robust building is more likely to be built correctly than a complex and robust building; in other words, choosing the simple building design might result in fewer process-induced building defects. The aspect "catastrophic loads for whole buildings" (RB4) evaluates how the finished building tolerates catastrophic loads, e.g. fire or earthquake. The aspect "energy class" for whole buildings (RB7) considers a separate method for classifying buildings in energy classes from A to G, where the results of the energy classification (NVE 2009) may be used directly in the robustness classification. The evaluation aspect "flexibility, ability to change floor plan and remodel" for whole buildings (RB8) considers whether the building's design and architecture allow for changes in the floor plan or for remodeling; the rationale is that a building with greater flexibility may have a more robust range of use than one with less flexibility.

The built-in flexibility of the robustness classification system allows the user to decide what emphasis to place on the various evaluation aspects by using different weight factors or even by deleting or adding specific aspects at various levels of building detail. That is, the robustness classification system is, itself, robust with respect to its range of use and flexibility.

5 CLIMATE CLASSIFICATION

Climate has a major influence on robustness and thus on a building's robustness class. Therefore, to evaluate robustness, we need to know the climate conditions to which the building and its components are exposed. For purposes of our classification system, this means we need a method to classify the total climate load before we can determine a building's robustness. Table 8 shows our proposed climate classes, which use the same seven-stage (A-G) grading system as our robustness and service life classes, along with three overarching climate categories: mild, moderate, and severe. The climate class is shown as a range in a climate index, with a scale opposite to the robustness scale, i.e. the lowest climate index number corresponds to the mildest climate. The higher the number on the 0-100 index, or the more advanced the climate class letter (A-G), the more severe the climate. That is, it is more challenging for materials, assemblies, and buildings to withstand, without degrading, climates denoted with higher numbers or more advanced letters. For example, climate class "G" (red) will be difficult for a material, assembly, or building to withstand. Climate class "A" (green) will be easy for a material, assembly, or building to withstand. The choice of climate class colours and grades (A-G) reflects the actual climate classes, not the robustness in that climate. The colour scheme is chosen in relation to determination of robustness class based on both climate class and service life class, as depicted in the examples in Table 12 and Table 13. The current climate classes (Table 8) and rating system (Table 9) are proposed and are still subject to refinement.

Table 8. Climate classification. The more advanced the letter denoting climate class (A to G), or the higher the number on the climate index (0-100), the more severe the climate and the more difficult it is for materials, assemblies, and buildings to withstand this climate without degrading.

	Mild climate			Moderate climate		Severe climate	
Climate class	**A**	**B**	**C**	**D**	**E**	**F**	**G**
Climate index	[0-10>	[10-20>	[20-40>	[40-60>	[60-80>	[80-90>	[90-100]

The climate classification procedure is approximately the same as the robustness classification procedure. The evaluation considers climate factors with corresponding weight factors (shown in Table 2). Rating of different climate factors from 0 (mild) to 100 (severe) is performed as shown in Table 9; i.e. the given rating for a climate factor and the corresponding climate index are equal. The products of ratings and weight factors (rating *x* weight factor) are summed up and normalized (the same principle as in Eq.1), which gives the climate index (from 0 to 100) and a climate class from "A" (mild) to "G" (severe). That is, the climate class is a range within the climate index.

Table 9. The rating of the different climate factors from 0 (extremely mild) to 100 (extremely severe). The basis of the rating is a quantitative evaluation of the climate factors. The table shows the corresponding climate class for individual climate factors.

	Mild climate			Moderate climate		Severe climate	
Climate factor evaluation	Extremely mild	Very mild	Mild	Mild to moderate	Moderate to severe	Severe	Extremely severe
Climate factor rating	[0-10>	[10-20>	[20-40>	[40-60>	[60-80>	[80-90>	[90-100]
Climate class of single climate factor	A	B	C	D	E	F	G

The climate indexes shown in Table 8 correspond to the proposed climate factor rating scheme in Table 9. The difference between the two is that the climate index considers the normalized sum of ratings, and the factor evaluation rating looks at individual climate factors.

6 CLIMATE CLASSIFICATION EXAMPLE

Table 10 shows an example of climate classification for Trondheim, Norway. The fixed weight factors are shown in Table 2. Table 9 shows the climate factor rating. The climate index is the normalized ratio between the sum of weighted ratings and the maximum possible sum. The corresponding climate class is found from Table 8. The result designates the climate in Trondheim as class "E", i.e. a moderate climate according to Table 8.

Table 10. Example of climate classification, for Trondheim, Norway. The applied weight factors and ratings are estimates, for purposes of demonstrating the classification method only.

Climate factors	Weighting factor (0-100)	Climate factor rating (0-100)	Climate class of single climate factor	Weighted rating
CF1: Solar and thermal infrared radiation	80	45	D	3 600
CF2: Temperature (high/low)	70	55	D	3 850
CF3: Temperature cycles	60	80	F	4 800
CF4: Air humidity	100	75	E	7 500
CF5: Water	100	65	E	6 500
CF6: Wind and air pressure	20	60	E	1 200
CF7: Erosion and corrosion	40	50	D	2 000
CF8: Pollution including micro-organisms	50	55	D	2 750
CF9: Synergies and oscillation	40	60	E	2 400
Sum	560	545		34 600
Maximum sum of weighted rating				56 000
Climate index – weighted	**62**		**Climate class**	**E**
Average rating (non-weighted)	61		i.e.	Moderate to severe

Background data for the climate factor ratings for Trondheim, Norway are as follows:

CF1: Solar and thermal infrared radiation. The radiation from sunlight in Trondheim is 871 kWh/(m^2·month) for a horizontal surface (SINTEF 472.411). This exposure is considered mild to moderate.

CF2: Temperature (high/low). Characteristic of the Nordic climate are mild summers and cold winters (about +20ºC to -20ºC). The mean temperature in Trondheim is 5.8ºC (SINTEF 451.021). Scheffer's index is 52, and the interval for medium decay risk is 35-65 (Lisø et al. 2006b). In sum, this climate factor is classified as mild to moderate.

CF3: Temperature cycles. Oscillating temperatures cause a larger number of freeze-thaw cycles in the north compared to a mid-European climate. This leads to greater decomposition of materials exposed to water. In Trondheim, the typical number of annual freeze-thaw cycles is 320 (Time et al. 2004). The frost decay index (FDEI) developed by Lisø et al. (2007) gives a value of 698.9, which is the fourth most severe condition among Norwegian towns. In sum, this climate factor is classified as severe.

CF4: Air humidity. The mean relative humidity in Trondheim is 78 % for the year (Geving and Thue 2002). Monthly values do not vary significantly from this. This factor is within the range of what is considered to be moderate to severe.

CF5: Water. The Nordic climate is rather humid. Trondheim has a mean annual precipitation of 892 millimeters (mm) (Time et al. 2004). Annual wind-driven rain for Trondheim is 368 mm/year (SINTEF 451.031). This is considered moderate to severe.

CF6: Wind and air pressure. Reference wind velocity is 26 m/s for Trondheim (SINTEF 471.043). The wind strain in Trondheim is considered moderate to severe.

CF7: Erosion and corrosion. Comprehensive study is required to assess erosion and corrosion, which may be highly local features. For Trondheim, this factor is estimated as mild to moderate.

CF8: Pollution including micro-organisms. The load from pollution depends strongly on local conditions, e.g. a street carrying a large volume of traffic will have more pollutants than quieter parts of town. This factor is set at mild to moderate for Trondheim.

CF9: Synergies and oscillation between conditions. Comprehensive study is required to determine synergies and oscillations. For this example, this factor is estimated as moderate to severe.

7 SERVICE LIFE CLASSIFICATION

Service life is a major component of robustness and thus has a significant influence on a building's robustness classification. We have proposed a simple method to classify service life to enable easy correspondence with robustness classifications. Table 11 shows our service life ranges. The service life classification method uses the same seven-stage (A-G) grading system as our robustness and climate classes, and also includes three overarching categories: short, moderate, and long service life. The service life ranges are proposed at this point and might be refined at a later time. In the service life grading system, the more advanced the letter (A to G), the longer the service life. Therefore, the more advanced the letter, the longer the materials, assemblies, and buildings must last without degrading. A service life class "G" (red) is difficult to achieve because it requires that a material, assembly, or building must last 100 years or more. A service life class "A" (green) requires that a material, assembly, or building last only up to one year. The choice of service life colours and grades (A-G) reflects the actual service life classes, not the robustness during that service life. The reasons for this colour scheme will be evident when the robustness class is determined with respect to both climate class and service life class, as depicted in the examples in Table 12 and Table 13. In some cases, a building might have a service life longer than 100 years, making it appropriate to use a defined service life class longer than the proposed final class G.

Table 11. Service life classes. The more advanced the letter (A to G), the longer the service life and the more difficult it is for materials, assemblies, and buildings to last as long as the specified service life without degrading.

	Short service life			Moderate service life		Long service life	
Service life class	**A**	**B**	**C**	**D**	**E**	**F**	**G**
Service life (years)	[0-1>	[1-5>	[5-10>	[10-20>	[20-50>	[50-100>	[100->

8 ROBUSTNESS CLASSIFICATION WITH RESPECT TO CLIMATE AND SERVICE LIFE

Table 12 and Table 13 show two examples of the use of the classification systems for climate, service life and robustness of a building or its parts. Following the same pattern as earlier, Table 12 and Table 13 are divided into seven robustness classes for each of the seven climate classes and seven service life classes, where each of the major three climate classes and three service life classes is represented as well. As noted earlier, the three classification systems use the same colours, i.e. dark green denotes a robust building or component, a mild climate, and a short service life. The information gathered in a matrix such as those shown in Tables 12 and 13 is quite comprehensive because each cell in the table represents a complete robustness classification incorporating both climate and service life. The item (material, assembly or building) evaluated in Table 12 becomes less robust with more severe climate and increasing (demand for a long) service life. Compared to the item in Table 12, the item in Table 13 is very robust in mild climates and somewhat robust in moderate climates, for a long service life. For severe climates, both the items in Table 12 and Table 13 are not particularly robust, especially for moderate and long service lives, i.e. we can assume that a significant decay process is initiated in a severe climate after a certain period (i.e., during a long service life), which dramatically decreases the robustness. We can see from these examples that the robustness classification as defined here is consistent throughout. Because the robustness classification system has robustness classes related to climate classes, a change in climate may lead to a change in climate class; thus, climate change is addressed by the robustness classification system.

Table 12. Example of the robustness for a specific item (material, assembly or building) in different climates and for different service lives. In a severe climate and for longer service life this item is less robust. Table 13 shows an item that is generally more robust.

				Robustness class						
Climate class	Severe climate	G	[90-100]	**D**	**E**	**F**	**F**	**G**	**G**	**G**
		F	[80-90>	**D**	**D**	**E**	**F**	**F**	**G**	**G**
	Moderate climate	E	[60-80>	**C**	**C**	**D**	**E**	**F**	**F**	**G**
		D	[40-60>	**B**	**C**	**C**	**D**	**E**	**F**	**G**
	Mild climate	C	[20-40>	**B**	**B**	**C**	**C**	**D**	**E**	**F**
		B	[10-20>	**A**	**B**	**B**	**C**	**C**	**D**	**F**
		A	[0-10>	**A**	**A**	**B**	**B**	**C**	**D**	**D**
				[0-1>	[1-5>	[5-10>	[10-20>	[20-50>	[50-100>	[100->
				A	B	C	D	E	F	G
				Short service life			Moderate service life		Long service life	
				Service life class (years)						

Table 13. Example of the robustness for a specific item (material, assembly or building) in different climates and for different service lives. In a severe climate and for longer service life this item is less robust. In general, this item is more robust than the item in Table 12.

				Robustness class						
Climate class	Severe climate	G	[90-100]	**A**	**B**	**C**	**F**	**G**	**G**	**G**
		F	[80-90>	**A**	**A**	**B**	**C**	**F**	**G**	**G**
	Moderate climate	E	[60-80>	**A**	**A**	**A**	**B**	**C**	**D**	**E**
		D	[40-60>	**A**	**A**	**A**	**A**	**A**	**A**	**A**
	Mild climate	C	[20-40>	**A**	**A**	**A**	**A**	**A**	**A**	**A**
		B	[10-20>	**A**	**A**	**A**	**A**	**A**	**A**	**A**
		A	[0-10>	**A**	**A**	**A**	**A**	**A**	**A**	**A**
				[0-1>	[1-5>	[5-10>	[10-20>	[20-50>	[50-100>	[100->
				A	B	C	D	E	F	G
				Short service life			Moderate service life		Long service life	
				Service life class (years)						

An alternative way of defining the robustness of a building or its parts is to state that a robust item must have a specified service life (e.g. 40 years or service life class "E"). This is illustrated in an example in Table 14 where the service life class is fixed and the robustness of the item is depicted in different climates. Table 14 represents the column in Table 12 that corresponds to service life class "E". The item in the example in Table 14 is robust (class "C") for the two mildest climate classes, "A" and "B".

Table 14. Example of the robustness for a specific item (material, assembly or building) in different climates. The table shows the column which represents service life class "E" (20-50 years) in Table 12.

Climate class and index			**Robustness class**	
Severe climate	G	[90-100]	**G**	Not ROBUST
	F	[80-90>	**F**	
Moderate climate	E	[60-80>	**F**	
	D	[40-60>	**E**	Less ROBUST
Mild climate	C	[20-40>	**D**	
	B	[10-20>	**C**	ROBUST
	A	[0-10>	**C**	

In some cases, the robustness of a building or its parts may only be relevant for the actual climate where it is located. In these cases it may be practical to fix the climate class and look only at different service life classes. Table 15 shows an example in which the climate class is fixed, and the robustness of the item is depicted for different service lives. Table 15 represents the row in Table 12 that corresponds to climate class "D". The item in the example in Table 15 is robust (class "B" and "C") for the three shortest service life classes, "A," "B" and "C".

Table 15. Example of the robustness for a specific item (material, assembly or building) for different service lives. The table shows the row that corresponds to climate class "D" (climate index 40-60) in Table 12.

	ROBUST			Less ROBUST		Not ROBUST	
Robustness class	**B**	**C**	**C**	**D**	**E**	**F**	**G**
Service life	[0-1>	[1-5>	[5-10>	[10-20>	[20-50>	[50-100>	[100->
Service life class	A	B	C	D	E	F	G
	Short service life			Moderate service life		Long service life	

9 ROBUSTNESS CLASSIFICATION EXAMPLES

The following subsections present examples of robustness classification of building materials, building assemblies and whole buildings. These examples are purely for the purpose of demonstrating the classification method, and the values given are estimates. The classification procedure is shown in greatest detail for a vacuum insulation panel (VIP) in the first example.

9.1 Classification example of a material: Vacuum insulation panel

A vacuum insulation panel (VIP) consists of an open, porous core of fumed silica enveloped in several metallized polymer laminate layers. VIPs represent today's state-of-the-art thermal insulation having thermal conductivities ranging from 3 to 4 mW/(mK) when new to typically 8 mW/(mK) after ageing for 25 years (due to diffusion of water vapour and air through the VIP envelope and into the open-pore structure of the VIP core material). The type of VIP envelope determines how much higher the thermal conductivity will be after 50 and 100 years of ageing. This inevitable increase in thermal conductivity is a major drawback of all VIPs. Puncturing of the VIP envelope, by nails or other sharp objects, increases the thermal conductivity to about 20 mW/(mK). As a result, VIPs cannot be cut for adjustment at the building site or perforated without losing a large part of their thermal insulation performance. This is another major disadvantage of VIPs. VIPs are also relatively costly. Despite these large disadvantages, VIPs are a large leap forward in thermal insulation for building applications compared to the approach of increasing wall or roof thicknesses to increase insulation performance because thick building envelopes would likely require new construction techniques and skills, and transport of thick building elements would increase costs (e.g. thinner elements may be transported for less cost than thicker elements that might not meet height restrictions for passing under bridges and through tunnels). Restrictions on retrofitting of existing buildings, e.g. by laws or codes or for practical reasons such as the dimensions of windows and other existing building parts, may also require thinner high-performance thermal insulation than is available with traditional insulation materials. Furthermore, in areas where floor space has a high market value per square meter, reduced wall thickness may keep significant floor area free compared to thicker walls, giving these buildings a higher value. Simple calculations show that, for such areas, the application of VIPs may actually result in an economic profit (Jelle 2011). For further information and details about VIPs, see e.g. Tenpierik (2009) and Baetens et al. (2010). With respect to robustness of VIPs themselves and VIPs applied in constructions, the recent studies by Wegger et al. (2011) and Sveipe et al. (2011) should be noted, treating ageing issues of VIPs, and retrofitting and condensation issues with VIPs, respectively.

Table 16 uses the proposed robustness classification system to analyze a 100 cm x 100 cm x 2 cm VIP with a multilayer foil (MF2) envelope. The chosen climate is class "E" (as in the example in Table 10), and the desired service life is class "F" (50-100 years). The classification process results in a designation of robustness class "E", i.e. less robust.

Table 16. Robustness classification example of a vacuum insulation panel (VIP). The rating of RM3 is taken from the separate evaluation shown in Table 17.

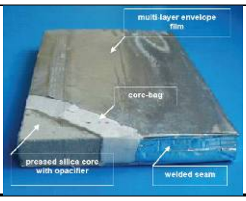
Evaluation Aspect		**Weight factor (0- 100)**	**Aspect rating (0- 100)**	**Robustness class of single aspect**	**Weighted rating**
RM1: Mechanical loads and various strains		60	35	G	2 100
RM2: Total climate load in the production phase		40	72	C	2 880
RM3: Durability, operational phase		100	58	E	5 768
RM4: Catastrophic loads		30	60	D	1 800
RM5: Installation/adaptation to its application		50	45	F	2 250
RM6: Range of use and usability		20	50	E	1 000
RM7: Environmental impact over lifetime		70	75	C	5 250
Sum		370	395		21 048
Maximum sum of weighted rating					37 000
Robustness value - weighted		**57**		**Robustness**	**E**
Average rating (non-weighted)		56		i.e.	Less ROBUST

Photo from Simmler et al. (2005). The item in the photo is an illustrative example, i.e. the calculated robustness value does not reflect the true robustness value of this specific item.

The various evaluations, resulting in a robustness class "E" for VIPs, are described in detail below, as is the basis (shown in Table 17) for the rating of aspect RM3, "Durability, operational phase" (applied as shown in Table 16).

RM1: Mechanical loads and various strains. A significant weakness of VIPs is their vulnerability to puncture. VIPs do not tolerate penetration by nails and cannot be cut and adapted at the building site. VIPs may be punctured in a number of ways during transport, storing, mounting and use. Therefore, this aspect is rated as *too poor* ("G").

RM2: Total climate load in the production phase. VIPs are produced in a controlled environment in factories and consist of materials that are resistant to the prevailing climate impacts. We can assume that the amount of moisture that is in the panel initially and the permeability of the panel are low. During implementation at the building site, VIPs may tolerate climate load quite well. Exposure to water during transport or storage may represent a problem, though. The tight VIP envelopes tolerate exposure to water for short periods, but long-time storage in a high-humidity climate will increase water vapour diffusion, thus accelerating a VIP's ageing. Exposure to water can be prevented by covering the VIP. The net result of VIPs' performance in relation to these various climate load issues is rated as *good* ("C").

RM3: Durability; toleration of total climate load during the operational phase. Table 17 shows the evaluation of this aspect and the resulting rating *moderate* ("E").

RM4: Catastrophic loads. Aside from fire resistance, VIPs have limited requirements related to extraordinary loads. VIPs can be laminated with a black glass fiber textile to enhance fire resistance and improve mechanical stability. VIPs are rated at flammability level B2 according to DIN4102 (Baetens et al. 2010). VIPs exhibit good tolerance for temporary water exposure, for example from an unexpected leak. In overall, VIPs are vulnerable to catastrophic loads, thus for this aspect VIPs are rated *fair* ("D").

RM5: Installation/adaptation to application. VIPs generally require careful design and mounting. In the Nordic climate, failure of a VIP has even larger consequences than in other climates, so it must be implemented with a high degree of accuracy to minimize the risk of condensation or puncture. In this climate, systematic quality assurance for every VIP before and after installation is recommended. Because of the degree of care required, for this apect VIPs are rated *poor* ("F").

RM6: Range of use and usability. The risk of puncture and the lack of adaptability reduce the range of use for VIPs. Nevertheless, if a VIP is fitted into an assembly where it is protected from damage, it may be part of a robust construction. In addition, the low thermal conductivity of VIPs allows for new, compact (thinner) building envelopes. Therefore, this aspect is rated *moderate* (“E”).

RM7: Environmental impact over lifetime. The environmental impact of VIPs varies depending on the life-cycle analysis (LCA) evaluation method used. VIPs have greater environmental impact than other thermal insulation materials because production of their silicon carbide core material is energy intensive (Binz et al. 2005). Nevertheless, a thermal insulation material saves a large amount of energy during the building’s lifetime. Taking all these factors into account, the rating for VIPs for this aspect is *good* (“C”).

Table 17 gives the background for the rating of aspect RM3 shown in Table 16. Table 17 also demonstrates how climate factors are used as evaluation aspects to determine a material’s climate load tolerance. Note that this robustness-to-climate evaluation is different from the climate class evaluation performed in Table 10.

Table 17. The basis for the rating of aspect RM3 as shown in Table 16. Climate factors are presented in Table 2.

Climate factor as Evaluation aspect	**Weight factor (0- 100)**	**Aspect rating (0- 100)**	**Robustness class of single aspect**	**Weighted rating**
CF1: Solar and thermal infrared radiation	80	80	B	6 400
CF2: Temperature (high/low)	70	40	F	2 800
CF3: Temperature cycles	60	55	E	3 300
CF4: Air humidity	100	50	E	5 000
CF5: Water	100	45	F	4 500
CF6: Wind and air pressure	20	95	A	1 900
CF7: Erosion and corrosion	40	75	C	3 000
CF8: Pollution including micro-organisms	50	60	D	3 000
CF9: Synergies and oscillation among conditions	40	60	D	2 400
	560	560		32 300
Maximum sum of weighted rating				56 000
RM3: Durability, operational phase	**58**		**Robustness**	**E**
Average rating (non-weighted)	62			

Similar to other forms of thermal insulation that are covered by building materials, VIPs are not expected to be exposed to substantial amounts of solar radiation. However, VIPs must tolerate the solar radiation exposure before they are installed in the building envelope. The solar radiation in Trondheim is 871 kWh/(m^2·month) for a horizontal surface (SINTEF 472.411). For the climate evaluation aspect *Solar and thermal infrared radiation (CF1),* VIPs in the Nordic climate are rated *very good* (“B”). In addition, the mean temperature in Trondheim is 5.8ºC (SINTEF 451.021), and the large temperature differences over the building envelope in wintertime in this climate make VIPs an especially attractive material solution because of their low thermal conductivity. The thermal bridges at the VIP edges and joints may pose a problem, however. A mild, cold (not warm) climate may actually result in increased durability of VIPs because diffusion of air into the panels depends strongly on temperature, i.e. larger diffusion at higher temperatures (Schwab et al. 2005) as air diffuses slowly into VIPs over time. The centre-of-panel thermal conductivity for a 100 cm x 100 cm x 2 cm MF2 (a specific multilayer foil) VIP envelope is 7.9 mW/(mK) after 50 years and 8.7 mW/(mK) after 100 years, which is an increase of 97.5 % and 117.5 %, respectively, from an initial conductivity value of 4.0 mW/(mK) (Baetens et al. 2010). See the works by Grynning et al. (2011), Sveipe et al. (2011) and Wegger et al. (2011) for various laboratory investigations of VIPs, the latter one addressing accelerated ageing of VIPs. Note that within this context it is chosen to evaluate these properties under the climate factor evaluation aspect *Temperature (CF2)* instead of under *Air pressure* (part of

CF6). The CF2 aspect may then obtain the rating *poor* (“F”). In the same manner the VIPs may be evaluated with respect to the other climate factors in Table 17.

9.2 Classification example of a material: Nano insulation material

A nano insulation material (NIM) is a possible future thermal insulation material presented conceptually by Baetens et al. (2010), Jelle et al. (2009) and Jelle et al. (2010). That is, a NIM is basically a homogeneous material with a closed or open small nano pore structure with an overall thermal conductivity of less than 4 mW/(mK) in the pristine condition. The NIMs obtain a very low thermal conductivity with either an open or a closed pore structure, due to the Knudsen effect where the mean free path of the gas molecules is larger than the pore diameter. That is, the NIM solid state structure does not need to prevent air and water vapour to diffuse into the pores, unlike the vacuum insulation panels (VIPs). Water condensation in the pores has to be avoided, though. Perforating the NIMs do not represent any problem, except the thermal bridges caused by the perforating agents (e.g. nails) themselves (like for all thermal insulation materials). Table 18 shows an example of robustness classification for a NIM of climate class “E” and service life class “F” (50-100 years), resulting in an overall robustness class “A” (robust).

Table 18. Robustness classification example of a material: Nano insulation material (NIM).

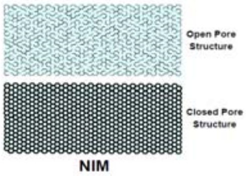
Evaluation aspect		**Weight factor (0- 100)**	**Aspect rating (0- 100)**	**Robustness class of single aspect**	**Weighted rating**
RM1: Mechanical loads and various strains		60	98	A	5 880
RM2: Total climate load in the production phase		40	95	A	3 800
RM3: Durability, operational phase		100	85	B	8 500
RM4: Catastrophic loads		30	85	B	2 550
RM5: Installation/adaptation to application		50	98	A	4 900
RM6: Range of use and usability		20	98	A	1 960
Environmental impact over lifetime		70	86	B	6 020
Sum		370	645		33 610
Maximum sum of weighted rating					37 000
Robustness value - weighted		**91**		**Robustness**	**A**
Average rating (non-weighted)		92		i.e.	ROBUST

Illustration from: Jelle et al. (2010).

9.3 Classification example of a material: Mineral wool

Table 19 shows an example of robustness classification of mineral wool for climate class "E" and service life class "F" (50-100 years), resulting in an overall robustness class "B" (robust).

Table 19. Robustness classification example of a material: Mineral wool.

Evaluation aspect		Weight factor (0- 100)	Aspect rating (0- 100)	Robustness class of single aspect	Weighted rating
RM1: Mechanical loads and various strains		60	92	A	5 520
RM2: Total climate load in the production phase		40	92	A	3 680
RM3: Durability, operational phase		100	85	B	8 500
RM4: Catastrophic loads		30	85	B	2 550
RM5: Installation/adaptation to application		50	88	B	4 400
RM6: Range of use and usability		20	85	B	1 700
RM7: Environmental impact over lifetime		70	82	B	5 740
Sum		370	609		32 090
Maximum sum of weighted rating					37 000
Robustness value - weighted		**87**		**Robustness**	**B**
Average rating (non-weighted)		87		i.e.	ROBUST

Photo from: http://www.glava.no/default.asp?page=505 (retrieved 17.12.2009). Note that the actual item in the photo is an illustrative example, and the calculated robustness value does not necessarily reflect the actual robustness value of this specific item.

9.4 Classification example of a material: Concrete

Table 20 shows an example of robustness classification of concrete for climate class "E" and service life class "F" (50-100 years), resulting in an overall robustness class "C" (robust).

Table 20. Robustness classification example of a material: Concrete.

Evaluation aspect		Weight factor (0- 100)	Aspect rating (0- 100)	Robustness class of single aspect	Weighted rating
RM1: Mechanical loads and various strains		60	85	B	5 100
RM2: Total climate load in the production phase		40	45	F	1 800
RM3: Durability, operational phase		100	83	B	8 275
RM4: Catastrophic loads		30	83	B	2 490
RM5: Installation/adaptation to application		50	85	B	4 250
RM6: Range of use and usability		20	92	A	1 840
RM7: Environmental impact over lifetime		70	65	D	4 550
Sum		370	538		28 305
Maximum sum of weighted rating					37 000
Robustness value - weighted		**77**		**Robustness**	**C**
Average rating (non-weighted)		77		i.e.	ROBUST

Photo from: http://www.inlandcanada.com/NR/rdonlyres/F0EBC912-01A0-4D58-AE7D-6F9FD7DE0FF7/0/ConcreteRecycler3.jpg (retrieved 17.12.2009). Note that the actual item in the photo is an example, and the calculated robustness value does not necessarily reflect the actual robustness value of this specific item.

9.5 Classification example of an assembly: VIP in sandwich element

Table 21 shows an example of robustness classification of an assembly built of wooden elements, vacuum insulation panels (VIPs), and wooden cladding in a sandwich configuration. For this example, this assembly must withstand the conditions of climate class "E" and service life class "F" (50-100 years). The VIP in the sandwich element obtained robustness class "C" (robust). That is, this example shows that VIPs can be more robust as part of an assembly than they are alone (compare with Table 16).

Table 21. Robustness classification example of an assembly: VIP in sandwich element.

Evaluation aspect		Weight factor (0- 100)	Aspect rating (0- 100)	Robustness class of single aspect	Weighted rating
Implementation phase					
RA1: Mechanical loads and various strains		30	45	F	1 350
RA2: Total climate load		30	78	C	2 340
RA3: Catastrophic loads		20	75	C	1 500
RA4: Ability to be built and/or implemented		40	70	C	2 800
RA5: Range of use and usability		40	55	E	2 200
Operational phase					
RA6: Mechanical loads and various strains		60	72	C	4 320
RA7: Durability; toleration of total climate load		100	76	C	7 613
RA8: Catastrophic loads		60	80	B	4 800
RA9: Ability to be replaced		30	50	E	1 500
RA10: Material match/interaction		50	92	A	4 600
RA11: Building physical aspects		10	82	B	820
RA12: Environmental impact over lifetime		100	75	C	7 500
Sum		570	850		41 343
Maximum sum of weighted rating					57 000
Robustness value - weighted		**73**		**Robustness**	**C**
Average rating (non-weighted)		71		i.e.	ROBUST

Photo from: Schäfer (2009). Note that the actual item in the photo is an example, and the calculated robustness value does not necessarily reflect the actual robustness value of this specific item.

9.6 Classification example of an assembly: Window

Table 22 shows an example of robustness classification of a window for climate class “E” and service life class “E” (20-50 years). The window obtained robustness class “D” (less robust).

Table 22. Robustness classification of an assembly: Window.

Evaluation aspect		**Weight factor (0- 100)**	**Aspect rating (0- 100)**	**Robustness class of single aspect**	**Weighted rating**
Implementation phase					
RA1: Mechanical loads and various strains		30	40	F	1 200
RA2: Total climate load		30	95	A	2 850
RA3: Catastrophic loads		20	45	F	900
RA4: Ability to be built and/or implemented		40	60	D	2 400
RA5: Range of use and usability		40	65	D	2 600
Operational phase					
RA6: Mechanical loads and various strains		60	50	E	3 000
RA7: Durability; toleration of total climate load		100	75	C	7 464
RA8: Catastrophic loads		60	45	F	2 700
RA9: Replaceability		30	85	B	2 550
RA10: Material match/interaction		50	80	B	4 000
RA11: Building physical aspects		10	75	C	750
RA12: Environmental impact over lifetime		100	65	D	6 500
Sum		570	780		36 914
Maximum sum of weighted rating					57 000
Robustness value - weighted		**65**		**Robustness**	**D**
Average rating (non-weighted)		65		i.e.	Less ROBUST

Photo from: http://www.etmv.com/2008/Feb08/PhotoWindowD.jpg (retrieved 17.12.2009). Note that the actual item in the photo is an example, and the calculated robustness value does not necessarily reflect the actual robustness value of this specific item.

9.7 Classification example of a building: Typical Norwegian timber frame building

Table 23 shows an example of robustness classification of a typical Norwegian timber frame building. The building must withstand climate class “E” and service life class “F” (50-100 years). The house obtained robustness class “C” (robust).

Table 23. Robustness classification example of a building: Typical Norwegian timber frame building.

Evaluation aspect		**Weight factor (0- 100)**	**Aspect rating (0- 100)**	**Robustness class of single aspect**	**Weighted rating**
Construction phase					
RB1: Catastrophic loads		30	70	C	2 100
RB2: Total climate load		20	75	C	1 500
RB3: Buildability		30	85	B	2 550
Operational phase					
RB4: Catastrophic loads		50	70	C	3 500
RB5: Durability; toleration of total climate load		100	76	C	7 612
RB6: Interaction of the different assemblies		20	90	A	1 800
RB7: Energy class		80	75	C	6 000
RB8: Flexibility; ability for change and remodeling		70	65	D	4 550
RB9: Building physical aspects		50	82	B	4 100
RB10: Environmental impact over lifetime		50	80	B	4 000
Sum		500	768		37 712
Maximum sum of weighted rating					50 000
Robustness value - weighted		**75**		**Robustness**	**C**
Average rating (non-weighted)		77		i.e.	ROBUST

Picture from: http://www.hortenhus.no/ (retrieved 17.12.2009). Note that the actual house in the photo is an example, and the calculated robustness value does not necessarily reflect the actual robustness value of this specific house.

9.8 Classification example of a building: Pyramid of Cheops

Table 24 shows an example of robustness classification of the Pyramid of Cheops. The climate class of Giza where the pyramid is located is not evaluated. The service life class is most definitely "G" (100 years and beyond). The Pyramid of Cheops received a robustness class designation of "B" (robust). This example illustrates very efficiently that for some cases, even for the more complex whole-building level of detail, it may be fairly easy to determine a high or low degree of robustness. In this case, the "Buildability" (RB3) and "Flexibility; ability for change and remodeling" (RB8) aspects received very low robustness scores (F and G, respectively), which reduces the total robustness score of an otherwise very robust building from class A to class B.

Table 24. Robustness classification example of a building : Pyramid of Cheops.

Evaluation aspect		**Weight factor (0- 100)**	**Aspect rating (0- 100)**	**Robustness class of single aspect**	**Weighted rating**
Construction phase					
RB1: Catastrophic loads		30	99	A	2 970
RB2: Total climate load		20	99	A	1 980
RB3: Buildability		30	45	F	1 350
Operational phase					
RB4: Catastrophic loads		50	95	A	4 750
RB5: Durability; toleration of total climate load		100	98	A	9 802
RB6: Interaction of the different assemblies		20	99	A	1 980
RB7: Energy class		80	95	A	7 600
RB8: Flexibility; ability for change and remodeling		70	10	G	700
RB9: Building physical aspects		50	90	A	4 500
RB10: Environmental impact over lifetime		50	100	A	5 000
Sum		500	830		40 632
Maximum sum of weighted rating					50 000
Robustness value - weighted		**81**		**Robustness**	**B**
Average rating (non-weighted)		83		i.e.	ROBUST

Photo from: http://www.molon.de/galleries/Egypt/Pyramids/images01/05%20Cheops%20pyramid.jpg (retrieved 17.12.2009).

10 CONCLUSIONS

We have presented a framework for a robustness classification method for building materials, building assemblies and whole buildings that takes into account climate and service life. Evaluation aspects with corresponding weight factors are proposed for three different levels of detail of a building: Materials, assemblies and whole buildings. We have demonstrated that, in principle, the classification method encompasses a complete overview of robustness at the three levels of detail. The robustness classification method have been applied more in detail to vacuum insulation panels (VIPs) as an illustrative example. Furthermore, the robustness classification method have been demonstrated for all three levels of detail for examples of building materials, building assemblies and whole buildings. The building materials which were classified were: Mineral wool, concrete, nano insulation materials (NIMs) and above-mentioned VIPs. The building assemblies classified were: A window and VIP in a sandwich element. The whole-building examples classified were: A typical Norwegian timber frame building and the Pyramid of Cheops. The chosen examples have demonstrated that the presented robustness classification framework has been designed with a versatile built-in flexibility. Forthcoming applications of the robustness classification at various levels of detail by different individuals and organizations will contribute to refine and finetune this framework further. The robustness classification framework will have a beneficial impact on all the various value segments within the building sector, hence influencing policies, strategies and practices, with robust buildings, including their materials and assemblies, as an ultimate result.

ACKNOWLEDGEMENTS

This work has been supported by the Research Council of Norway and several partners through the SINTEF and NTNU research projects ”*Robust Envelope Construction Details for Buildings of the 21st Century*” (ROBUST) and ”*The Research Centre on Zero Emission Buildings*” (ZEB).

REFERENCES

R. Baetens, B. P. Jelle, J. V. Thue, M. J. Tenpierik, S. Grynning, S. Uvsløkk and A. Gustavsen, ”Vacuum insulation panels for building applications: A review and beyond”, *Energy and Buildings*, **42**, 147-172, 2010.

A. Binz, A. Moosmann, G. Steinke, U. Schonhardt, F. Fregnan, H. Simmler, S. Brunner, K. Ghazi, R. Bundi, U. Heinemann, H. Schwab, J. M. Cauberg, M. J. Tenpierik, G. Johannesson, T. Thorsell, M. Erb and B. Nussbaumer, ”Vacuum insulation in the building sector. Systems and applications (Subtask B)”, Final report for the IEA/ECBCS Annex 39 HiPTI-project, 2005.

C. Brischke, R. Bayerbach and A. O. Rapp, ”Decay-influencing factors. A basis for service life prediction of wood and wood-based products”, *Wood Material Science and Engineering*, **1:3**, 91-107, 2006.

E. U. Choo, B. Schoner and W. C. Wedley, ”Interpretation of criteria weights in multicriteria decision making”, *Computers & Industrial Engineering*, **37**, 527-541, 1999.

S. Geving, and J. V. Thue, ”Fukt i bygninger” (Moisture in buildings), SINTEF Building and Infrastructure, Norway, 2002.

S. Grynning, B. P. Jelle, S. Uvsløkk, A. Gustavsen, R. Baetens, R. Caps and V. Meløysund, ”Hot box investigations and theoretical assessments of miscellaneous vacuum insulation panel configurations in building envelopes”, *Journal of Building Physics*, **34**, 297-324, 2011.

S. E. Haagenrud, ”Environmental characterisation including equipment for monitoring”, CIB W80/RILEM 140-PSL, SubGroup 2 Report, 1997.

H. T. Harket, ”Energimerking av bygg” (Energy labelling of buildings), No.2, 2009, Norges vassdrags- og energidirektorat, NVE (Norwegian Department of Waterway and Energy), 2009.

ISO 6707-1:2004(E) (2000), ”Building and civil engineering - Vocabulary - Part 1: General terms”, 2004.

ISO 15686-1:2000(E) (2000), ”Buildings and constructed assets – Service life planning - Part 1: General principles”, 2000.

B. P. Jelle, T.-N. Nilsen, P. J. Hovde and A. Gustavsen, ”Accelerated climate ageing of building materials and application of the attenuated total reflectance (ATR) Fourier transform infrared (FTIR) radiation experimental method”, *Proceedings of the 8th Symposium on Building Physics in the Nordic Countries*, Volume 2, C. Rode (Ed.), pp. 951-958, Copenhagen, Denmark, 16-18 June, 2008, Danish Society of Engineers, Copenhagen, 2008.

B. P. Jelle, A. Gustavsen and R. Baetens, ”Beyond vacuum insulation panels - How may it be achieved?”, *Proceedings of the 9th International Vacuum Insulation Symposium (IVIS 2009)*, London, England, 17-18 September, 2009.

B. P. Jelle, A. Gustavsen and R. Baetens, ”The path to the high performance thermal building insulation materials and solutions of tomorrow”, *Journal of Building Physics*, **34**, 99-123, 2010.

B. P. Jelle, K. Noreng, T. H. Erichsen and T. Strand, ”Implementation of radon barriers, model development and calculation of radon concentration in indoor air”, *Journal of Building Physics*, **34**, 195-222, 2011.

B. P. Jelle, ”Traditional, state-of-the-art and future thermal building insulation materials and solutions - Properties, requirements and possibilities”, *Energy and Buildings*, **43**, 2549-2563, 2011.

B. P. Jelle, T.-N. Nilsen, P. J. Hovde and A. Gustavsen, ”Accelerated climate aging of building materials and their characterization by Fourier transform infrared radiation analysis”, *Journal of Building Physics*, **36**, 99-112, 2012.

B. P. Jelle, ”Accelerated climate ageing of building materials, components and structures in the laboratory”, *Journal of Materials Science*, **47**, 6475-6496, 2012(a).

B. P. Jelle, ”Development of a model for radon concentration in indoor air”, *Science of the Total Environment*, **416**, 343-350, 2012(b).

K. R. Lisø, T. Kvande and J. V. Thue, ”The robustness of the Norwegian building stock - A review of process induced building defects”, *Proceedings of the 7th Symposium on Building Physics in the Nordic Countries*, G. Jòhannesson (Ed.), The Icelandic Building Research Institute, Reykjavik, pp. 1195-1202, 2005.

K. R. Lisø, ”Building envelope performance assessments in harsh climates: Methods for geographically dependent design”, *Ph.D. thesis* 2006:185, Norwegian University of Science and Technology (NTNU), Department of Civil and Transport Engineering, 2006(a).

K. R. Lisø, H. O. Hygen, T. Kvande and J. V. Thue, ”Decay potential in wood structures using climate data”, *Building Research & Information,* **34**, 546-551, 2006(b).

K. R. Lisø, T. Kvande, H. O. Hygen, J. V. Thue and K. Harstveit, ”A frost decay exposure index for porous, mineral building materials”*, Building and Environment*, **42**, 3547-3555, 2007.

NS 3491-4, ”Prosjektering av konstruksjoner - Del 4: Vindlaster” (Design of constructions - Part 4: Wind loads), 2002.

NVE 2009, ”Energimerkeskalaen (18.11.2009)” (The energy rating scale (18th of November 2009), Norges vassdrags- og energidirektorat, NVE (Norwegian Department of Waterway and Energy), http://www.bygningsenergidirektivet.no/no/Energimerking-Bygg/Om-energimerkesystemet-og-regelverket/Energimerkeskalaen/, Retrieved 17.12.2009.

M. E. Qureshi and S. R. Harrison, ”Application of the analytic hierarchy process to riparian revegetation policy options”, *Small-Scale Forest Economics, Management and Policy*, **2**, 441-458, 2003.

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

W. Schäfer, ”Schlank und glänzend verpackt”, Bauen mit Holz, no. 1, pp. 26-29, 2009.

H. Schwab, U. Heinemann, H. P. Ebert and J. Fricke, ”Permeation of different gases through foils used as envelopes for vacuum insulation panels”, *Thermal Envelope and Building Science*, **28**, 293-317, 2005.

H. Simmler, S. Brunner, U. Heinemann, H. Schwab, K. Kumaran, P. Mukhopadhyaya, D. Quènard, H. Sallèe, K. Noller, E. Kücküpinar-Niarchos, C. Stramm, M. Tenpierik, H. Cauberg and M. Erb, ”Vacuum insulation panels. Study on VIP-components and panels for service life prediction in building applications (Subtask A)”, *HiPTI - High Performance Thermal Insulation, IEA/ECBCS Annex 39*, September, 2005.

SINTEF 451.021, SINTEF Building Research Design Sheets no. 451.021, ”Klimadata for termisk dimensjonering og frostsikring” (Climate data for thermal design and frost prevention), SINTEF Building and Infrastructure, Norway, 2009.

SINTEF 451.031, SINTEF Building Research Design Sheets no. 451.031, ”Klimadata for dimensjonering mot regnpåkjenning” (Climate data for precipitation dependent design), SINTEF Building and Infrastructure, Norway, 2007.

SINTEF 471.043, SINTEF Building Research Design Sheets no. 471.043, ”Vindlaster på bygninger” (Wind loads on buildings), SINTEF Building and Infrastructure, Norway, 2003.

SINTEF 472.411, SINTEF Building Research Design Sheets no. 472.411, ”Solstrålingsdata for energi- og effektberegninger” (Sun radiation data for energy and power calculations), SINTEF Building and Infrastructure, Norway, 1991.

E. Sveipe, B. P. Jelle, E. Wegger, S. Uvsløkk, S. Grynning, J. V. Thue, B. Time and A. Gustavsen, ”Improving thermal insulation of timber frame walls by retrofitting with vacuum insulation panels – Experimental and theoretical investigations”, *Journal of Building Physics*, **35**, 168-188, 2011.

M. J. Tenpierik, ”Vacuum insulation panels applied in building constructions (VIP ABC)”, *Ph.D. Thesis*, Delft University of Technology, Delft, The Netherlands, 2009.

B. Time, T. Kvande, K, Terjesen and Ø. Sæter, ”Fukttransport i mineralske bygningsmaterialer - Materialegenskaper” (Moisture transport in mineral building materials - Material properties), Project report 369, SINTEF Building and Infrastructure, Norway, 2004.

E. Wegger, B. P. Jelle, E. Sveipe, S. Grynning, A. Gustavsen, R. Baetens and J. V. Thue, ”Aging effects on thermal properties and service life of vacuum insulation panels”, *Journal of Building Physics*, **35**, 128-167, 2011.