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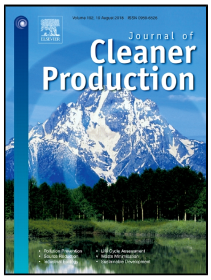

Assessment of greenhouse gas emissions of ventilated timber wall constructions based on parametric LCA

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Assessment of greenhouse gas emissions of ventilated timber wall constructions based on parametric LCA

1. Introduction

The building sector is a large contributor to global energy use and greenhouse gas (GHG) emissions, consuming approximately 2/5 of global energy and contributing to 1/3 of global GHG emissions (IEA 2013). With increased efforts in mitigating global climate change and promoting sustainable development, the building sector has become a main target aimed at enhancing energy efficiency and utilizing renewable materials and energy technologies which resulted in reduction in GHG emissions from operational energy. In contrast, the embodied GHG emissions arising from production, construction, maintenance, replacement and demolition phases are gaining significance (Ibn-Mohammed et al. 2013, Trabucco and Wood 2016). Consequently, there is a growing interest in addressing embodied energy and choosing low-carbon products when designing energy efficient buildings. Life cycle assessment (LCA) is a well-established methodology used to assess the environmental performance of buildings in a holistic approach.

The embodied GHG emission results from two virtual models, and five zero emission building (ZEB) pilot buildings from the Norwegian ZEB research center case studies show that the building envelope (ca. 65%) and production and replacement of materials (ca. 55-87%) are the main contributors to total GHG emissions across the Norwegian ZEB case studies (Wiik et al. 2018). Development of low carbon design strategies that includes selection of locally available building materials with application of reused and recycled materials, longer service life and lower embodied GHG emissions are considered as one measure for reducing emissions over life cycles of buildings (Ingrao et al. 2016, Fufa et al. 2017 , Jelle et al. 2017). The use of timber products, sourced from responsibly managed forests, in place of traditionally high-embodied GHG emission materials in buildings in general and wall constructions in particular have been considered as effective means to reduce fossil energy use and carbon footprint. The reasoning for this is partly that the production has a lower impact than comparable materials and partly because wood stores CO_2 (Sathre and Gustavsson 2009, Guest et al. 2013, Dodoo et al. 2014).

Interest has been growing around the world in the design and construction of taller timber buildings due to the need for green and sustainable architecture, driven by different stakeholders who see timber as a positive solution given the sustainable credentials it offers (Barber 2015, Bowyer et al. 2016). The increased use of multi-storey timber buildings can possibly create a significant reduction on the life cycle environmental impact of a building.

As a natural material, wood is much more moisture sensitive and based on detrimental moisture susceptible to fungi and decay. As long as dry conditions can be secured, timber is one of the most durable material. However, with an increasing height of timber buildings one of the challenge is to provide dry conditions for the expected lifetime of the building (Lolli et al. 2017, Tietze et al. 2017). Tall buildings are particularly exposed to high wind pressures combined with wind driven rain. Additionally, on site construction of tall buildings require longer times of construction in which the structural elements are especially exposed to moisture. The penetration moisture through the wall construction can cause decay and mould growth, which results in poor indoor air quality, health problem,premature structural failure, additional costs and GHG emissions arising from the removal, repair, or replacement of damaged parts or entire components. Furthermore, inspection, maintenance and repair possibilities are limited in high-rise structures. Compared to fire safety and static demands, the risk of moisture damages today is dramatically underestimated in planning, building processes, and quality management (Tietze et al. 2017). The variety of configurations of the wall construction and the diversity of the effects of external and internal climate in the early planning and building process need assistance in selection of low embodied carbon material and design options. Parametric analysis is a useful tool, used to facilitates for the dynamic evaluation and comparison of multiple alternative scenarios simultaneously.

The objective of this work is to present a parametric LCA tool specifically developed to evaluate the potential environmental impact of moisture induced damage scenarios around window connections of timber wall constructions. Exemplary ventilated timber wall constructions from four countries are used as a case. The parametric LCA approach embed probabilistic-based design methodology to evaluate the probability of moisture damage risks, expressed in mould and decay growth occurrence for different case scenarios, and the consequence of damage, which are expressed in GHG emissions. For each alternative, embodied GHG emissions are calculated.

To follow, the methodology section presented the wall construction used in the study. It also outlines the LCA methodology, parametric analysis and the probability of a failure calculation. Next, the results and possible future perspectives are discussed. Finally, the conclusion outlines the contribution of the study.

2. Methodology

The methodology section of this paper is divided into four parts. The first part presents four typical ventilated wall constructions considered in the study. The second part outlines the life cycle assessment (LCA) methodology used to evaluate the embodied GHG emissions due to the potential moisture damage. It includes a description of goal and scope, the background data used and assumptions considered in the LCA study. The third part describes three parameters considered to evaluate the effect of moisture around window connections. The fourth part describes the probabilistic-based design methodology that assesses the performance of wall constructions against mould and decay growth and accounts for the aforementioned uncertainties.

2.1 Description of wall constructions

In this study, ventilated timber wall constructions commonfor Norway (NO), Germany (DE), Sweden (SE) and France (FR), are considered (Table 1). The four countries were chosen as they involved in the European project, TallFacades, on which this study is carried out. A ventilated timber wall construction is less common than using massive timber constructions consisting of a solid load-bearing wooden element (often Cross-Laminated Timber, CLT) and a separate layer for insulation. This construction has been selected because ventilated timber wall constructions have a larger field of application than massive timber construction as they are used as a load-bearing wall and also can be applied as curtain wall in so-called hybrid structures (Tietze et al. 2017).

Since insulation and load-bearing structure are in the same layer, the exterior parts of the wooden beams are exposed to a relatively cold climate and consequently to a high relative humidity. Furthermore, a ventilated timber wall is more complex with respect to building physics and building construction due to its numerous layers such as additional layers to provide air tightness and vapour tightness. Whilst, the CLT element in a massive construction can be used as air barrier and vapour barrier besides its load-bearing function. Thus, it will be easy to transfer all methods and findings of the project to the less complex system of a massive timber construction.

The geometry of the wall constructions from each country and relevant material properties considered in the LCA and probability of failure analysis are given in Table 1. The potential impact of moisture damage of windows on GHG emission and probability of failure of mould and decay growth occurrence on the windows themselves is not considered given our primary focus on the basic wall components. However, a simplified calculation is performed to evaluate the impact from windows by multiplying the wall quantities and number of windows with the average emission factor of windows (given in Table 2) obtained from environmental product declarations (EPD).

2.2 GHG emissions calculation

The LCA is performed in accordance with the principles and framework for LCA as defined by the international standard for LCA ISO 14040/44 (ISO 14040 2006, ISO 14044 2006), the European standard for the assessment of the environmental performance of buildings EN 15978 (EN 15978 2011) and the European standard for Environmental Product Declarations (EPD) core rules for product category of construction products EN 15804 (EN 15804 2012).

The LCA methodology follow the requirements and guidelines of ISO 14040 /44 and consists four steps: definition of goal and scope, life cycle inventory, life cycle impact assessment and interpretation of the results. The goal of LCA is to investigate the environmental impact of different potential moisture-related damage scenarios in four timber wall constructions form Germany (DE), France (FR), Norway (NO) and Sweden (SE) over the building life cycle. The functional unit is represented by $1m^2$ wall over the 50 year estimated service life of the building.

The system boundary of the study is defined according to the modular life cycle system as defined in EN 15978 (Figure 1) (EN 15978 2011). The modular life cycle system measures the cradle-to-grave impacts from four main life cycle stages: Product stage (modules A1-A3), construction stage (modules A4-A5), use stage (modules B1-B7) and end-of-life (modules C1-C4). In addition, the optional stage (module D) is defined to account for the potential positive impacts of processing or reuse of materials after end-of-life. In this study, modules A1-A3, A4-A5, B4 and C1-C4 are included.

The life cycle environmental impact is calculated in terms of Global warming potential (GWP) (measured in CO_{2eq}) throughout the life cycle of the wall constructions. Embodied GHG emission factors for A1-A3 life cycle stages are obtained from product specific EPD data, compliant with EN 15804 (Table 2). A simplified scenarios and generic ecoinvent v3.1 (Ecoinvent 2014) data has been developed for A4-A5, B4 and C1-C4 life cycle modules. The life cycle inventory used in the LCA is further elaborated in sections 2.2.1- 2.2.4.

The ecoinvent system model *allocation cut-off by classification* (also known as *recycled content*) is used, as this uses the same allocation for recyclable materials as is used in EPDs compliant with EN 15804 (EN 15804 2012). SimaPro version 8.0.4.30 is used to calculate the LCIA results based on ecoinvent data. The biogenic carbon content of wood based materials is excluded in the calculation, due to the assumptions that 1) all wood is from sustainably managed forests and 2) instant oxidation of the biogenic carbon (i.e. that all emissions occur in year 0 and that potential methane emissions from anaerobic oxidation are disregarded). This choice is in accordance with current EPD approaches (PR CEN/TR 16970 2016).

The interpretation of the GHG emission results presented in Chapter 3. It should be noted here that the objective of this work is not to compare GHG emission results of wall constructions between the four countries. Rather, it is to show how parametric LCA tool will enable the evaluation of different parameters that can occur due to the potential impact of moisture damage on GHG emissions of wall constructions.

2.2.1 Product stage (A1-A3)

An average EPD data of relevant EPDs selected mainly from the Norwegian EPD programme operator (EPD-Norway) are used as a data source for A1-A3 (Table 2). The data from EPD-Norway is up to date and are compliant with construction product category rules, EN 15804, which is a core for construction product EPDs (EN 15804 2012). EPD-Norway has mutual agreement with programme operators from Germany (IBU) and Sweden (the International EPD System), that means they acknowledge that the EPDs are comparable. In addition, EPD-Norway and EPD programme operators from Germany, Sweden and Fance (INIES) are part of the European ECO Platform collaboration (Eco Platform).

The average weight of the products and GHG emission factors along with the background data such as total number of EPDs used, the reference number of the EPDs and a description of selection criteria are listed in Table 1. For wood based products and products which contains wood, an average EPD data excluding biogenic carbon (amount of CO_2 uptake by bio-based products) is used. For exterior wooden cladding, an average of EPDs of treated wood is used. An average EPDs of 12.5mm gypsum board used for interior claddings are considered. For insulation, an average EPDs of glass wool insulation is used. Even if the potential impact of moisture damage of windows on GHG emissions of wall construction are not evaluated in this study, emissions related to window are included. The average EPD data for windows with aluminium cladding is used.

2.2.2 Construction stage (A4-A5)

The GHG emissions calculation from the construction stage include the emissions from the transportation of the materials from the factory gate to the building site (A4) and the construction installation process (A5).

Transport (A4): The GHG emissions from A4 are calculated using the distance from production site to the construction site, weight of the materials and emission factor from means of transportation. The building site is assumed to be located in Oslo for the NO wall construction, Frankfurt for the wall construction from DE, Stockholm for SE wall construction and Paris for wall construction from FR. 200 km is assumed as an average transport distances from manufacturing site to building site. Average product weight collected from EPDs (see Table 2) are considered in the calculation. The emission factor from Ecoinvent v3.1 process "*Transport, freight, lorry 16-32 metric ton, EURO4 (Feist et al.) | Alloc Rec*" is chosen as a default for road transport.

Construction installation (A5): For A5, the GHG emissions from material loss, internal construction site transport, transport of auxiliary materials, machineries and waste and energy use during onsite construction/installation process are considered. In this study, we have assumed GHG emissions related to construction site activities as 10% of total GHG emissions based on the recent Norwegian ZEB centre study on GHG emission from construction site performed using actual construction on site data (Wiik et al. 2017 , Fufa et al. 2018 forthcoming).

2.2.3 Use stage

Replacement (B4): The GHG emissions calculation from the use stage consider B4. A building service life of 60 years is used in NO, whereby 50 years is considered as common practice in GE, FR and SE. In this study, the service life of the building is considered as 50 years for evaluation of all wall constructions. The actual EPD data is used without converting the emission results for 50 years. The service life for materials is mainly based on the information obtained from EPDs.

2.2.4 End-of-life (C1-C4)

The GHG emissions calculation from end-of-life (EoL) include GHG emissions from deconstruction (C1), transport to waste processing site (C2), waste processing (C3) and waste disposal (C4). Ecoinvent data have been used in combination with Statistics Norway (SSB) information to calculate the LCIA results. The reason for this is twofold. The first is that EoL is optional and thus not included in all EPDs. The second is that EoL is based on scenarios and using ecoinvent provides a consistent modelling of the EoL between the countries.

Deconstruction (C1): The GHG emissions associated with the energy use in C1 have been assumed to be identical to A5. This is also found to be a common approach used in the sourced EPDs. In this study, A5 consider GHG emissions related to material loss, internal construction site transport, transport of auxiliary materials, machineries and waste and energy use during onsite construction/installation process. According to the Norwegian ZEB centre report (Wiik et al. 2017), the energy use during construction stage is responsible to about 50% of the total construction stage emissions. Thus, in this work we have considered the energy use for deconstruction is 50% of the GHG emissions from A5.

Transport to waste processing site (C2): A transport distance of 50 km from the building site to the nearest recycling or incineration site and 50 km to the nearest landfill is assumed. Trucks are considered as means of transportation. The emission factor from Ecoinvent v3.1 process for transport "*Transport, freight, lorry 16-32 metric ton, EURO4 (Feist et al.) | Alloc Rec*" is chosen as a default.

Waste processing (C3) & Waste disposal (C4): For each material three possible EoL routes have been calculated: incineration, landfill, and recycling. The amount of materials going to each EoL route are allocated based on the waste treatment data from Statistics Norway (SSB) (SSB 2016). The GHG emissions have been calculated using generic processes from Ecoinvent v3.1 (see Figure 2 and Figure 3).

For incineration, these are specific for material groups (e.g. wood, plastic, inert materials). For landfill, processes are identical for all types of materials (see Figure 3). Materials for recycling leave the system after transportation to recycling facility in module C2, when they are considered to have reached the end-of-waste state. Note that the municipal solid waste incineration is identical between the four countries. This is because ecoinvent uses the same underlying process for all the countries.

As for municipal solid waste incineration, waste landfill is also identical between the four countries (see Figure 3). Please note the difference in scale from incineration. This difference is the reason it is included in its own figure, as landfill is approximately 1 % of the impact of municipal incineration.

2.3 Description of parameters

Three parameters are considered to create scenarios that show different levels of moisture damage to the wall/window connections and the consequences. The parameters used to evaluate the performance of the wall constructions include i) number of window, ii) the extent of damage around the window connections and iii) the number of of damaged wall components. The summary of the parameters used in this study is given in Table 3. The assumptions and calculation methodologies used to calculate the parameters are summarised in the following sections.

2.3.1 Number of windows

The possible maximum number of windows in the given area of wall (Awall=24m^2) of a ventilated timber frame wall constructions from each of the four countries have been calculated. A window area of 1.82m^2 (with a dimension of 1.23m x 1.42m) is considered in accordance with EN 14351-1.The area of windows (Awindow) is assumed to be of a fixed size for all countries. The maximum number of window per area of the wall was calculated assuming 22% of window to wall ratio (WWR). Here it should be noted that the number of window requirements are typically dependent on the floor area, not the wall area. This gives a maximum of 3 windows in the reference 24m^2 wall area ((0.22*24m^2)/1.82m^2= 3). Thus the following four scenarios are considered to evaluate the effect of number of windows:

- Scenario 1: 24m^2 wall without window
- Scenario 2: 22.18m^2 wall with 1 window
- Scenario 3: 20.36m^2 wall with 2 windows
- Scenario 4: 18.54m^2 wall with 3 windows

Note that in this study only the probability of damage related to wall components, excluding the potential impacts of moisture damage of windows on the GHG emissions of wall construction, are considered. That means, for example for a wall with 3 windows, 18.54m^2 wall area is considered when evaluating the potential area of replacement and number of replaced layers after subtracting the area of the three windows (24m^2 - (3*1.82m^2) = 18.54m^2). However, the impacts related to A1-A3, A4-A5 and C1-C4 life cycle stages of window is included in the analysis.

2.3.2 Area of replacement

The extent of damage due to moisture around the window connections is expressed by different percentage of the length around the window that is impacted by the damage. The extent is thus calculated assuming 100% damaged wall area below the window, 50% damaged wall area on the two sides of the window and 20% damaged wall area on the top of the window (see Figure 4).

This gives a maximum damaged area of 3.49m^2 for a wall with 1 window (about 16% of the wall area) 6.97m^2 for a wall with 2 windows (about 34% of the wall area) and 10.45m^2 for a wall with 3 windows (about 56% of the wall area). Thus, the extent of damage is evaluated by considering 20%, 40%, 50%, 75% and 100% of the calculated maximum damaged area (3.49m^2) which need replacement. This gives the following scenarios to evaluate the effect of area of replacement: 0.70m^2; 1.40m^2; 1.75m^2; 2.62m^2 and 3.49m^2.

2.3.3 Number of damaged layers

The moisture damage is assumed to propagate from outside (external cladding) to the 4th layer of each of the wall construction. That means, the number of layers from external cladding (layer 1) to the 4^{th} or 5^{th} layers are assumed to be replaced due to the moisture damage. Thus, the following scenarios are considered to evaluate the effect from the number of damaged wall components that need replacement:

- Scenario 1: replacement of layer 1
- Scenario 2: replacement of layer 1 and 2
- Scenario 3: replacement of layer 1, 2 and 3
- Scenario 4: replacement of layer 1, 2, 3 and 4/5

Table 4 provides an overview of which of the first 6 layers included in the damage assessment for each country.

Some layers (marked with an asterisk (*) in Table 4) are assumed not to be replaced because replacing these layers is complicated as they are crucial for the functioning of the wall and often made of moisture-sensitive materials. These layers include load bearing structural material (wood stud in all wall constructions), the 6^{th} interior layer (vapour barrier (for Norwegian and Swedish wall) or OSB (for Germany wall)) and the insulation layer (for France wall).

2.4 Simulation set-up and calculation of probability of failure

The parametric LCA provides information about the consequences of a potential failure event. The next step is to calculate the probability of a failure, which in the present study is considered as the mould or decay occurrence on the interface of the wall construction layers'. The failure event is defined as exceedance of mould growth intensity that endangers the integrity of the wall construction in terms of the GHG emission consequences.

Mould is a very complex biological phenomenon, which is highly dependent of the interrelation between humidity, temperature, time and material characteristics (Gradeci et al. 2018).The repeated mould growth problems in buildings industry suggest that the representation and prediction of mould growth are associated with large uncertainties related to the representation of the biological phenomenon, the climate exposure and the material uncertainties. Probabilistic-based approaches can account for these uncertainties, and therefore improve the design of wall constructions with an adequate degree of reliability (Gradeci et al. 2016).

A probabilistic-based design methodology (Gradeci et al. 2016, 2018) is applied to calculate the probability of mould and decay (only for wood-based materials) occurrence in the first four interfaces of each wall construction. The causal relationships that affect this mechanism and subsequently the influencing parameters are identified. These factors include relative humidity, temperature, time and substrate, whilst the input parameters affecting these factors include weather conditions, indoor climate, as well as the material properties of the wall construction. The probabilistic models account for the uncertainties of both design parameters (the parameters that are manageable during the design stage including wall construction material properties) and non-design parameters (for example the outdoor or indoor climate exposure).

The heat and moisture simulations are performed using the hygrothermal building simulation software WUFI®(Hartwig Michael Künzel 1995). This model calculates the temperature and relative humidity in the building components, as developed by Fraunhofer IBP and validated by numerous research studies. Time series analysis using ARMA (Autoregressive-Moving

Average) models are applied to construct the outdoor weather simulations (Gradeci et al. 2016) with a duration similar to the expected service life of the façade constructions (50 years). This is because of the convergence of the probability of failure is reached already before exceeding 50 years. The indoor climate used in this study is represented by a sine wave derived from a single year period representing moisture load categories according to WUFI. The mean air temperature is 21°C with an amplitude of 1°C. Considering material's uncertainties fall out of this work's scope.

Mould growth and decay degree are calculated using the VTT model (Viitanen and Ojanen 2007, Ojanen et al. 2010) and Logistic dose–response performance model (LDR), respectively. These two empirical models can calculate the mould growth and decay rating as a function of the time history of the hygrothermal conditions (temperature and relative humidity) on each interface based on the selected substrate category. The 'Very Sensitive' category is chosen to assess mould germination. Currently, there are no established guidelines regarding design criteria against mould and decay. Therefore, three different levels of mould growth are considered as the failure borderline for a duration of 50 years: mould index I, II and III according to (Viitanen and Ojanen 2007, Ojanen et al. 2010). Failure is considered either the onset of decay or one of the mould growth levels. A log-normal distribution is fitted to the results for 100 samples for each of the investigated layers.

3. Results and discussions

3.1 Parametric LCA without mould occurrence probability

This part presents the total GHG emissions from four wall constructions per life cycle stages (section 3.1.1.) and total GHG emissions for different scenarios considered in this study (section 3.1.2).

3.1.1 Total GHG emissions per life cycle stage

Figure 5 show total GHG emissions per m^2 of the wall construction from each country per each life cycle stage. For window, the total GHG emission results from A1-A5, B4 and C1-C4 are shown in the Figure 5. The GHG emission results per life cycle of window are shown in Figure 6.

The results in Figure 5 include the impact for the base case scenario (for the case of no window and no moisture damage) and for different scenarios considered for number of window, damage area and replaced layers. The impact from the probability of mould growth is not included in this analysis. For the base case scenario, the product stage (A1-A3) is the main GHG emission contributor followed by waste treatment (C3), installation (A5), transport A4, deconstruction (C1), transport to waste treatment (C2), whilst the impact from waste disposal (C4) is negligible. For the base case scenario, the impact from replacement (B4) is zero as there is no replacement is needed due to 60 years service life of materials used in the wall construction. The GHG emissions per each life cycle module results show GHG emissions per m^2 wall for each life cycle stage is the same for all scenarios except for the replacement module (B4) in the use stage

The results show that, the total GHG emissions from the four wall constructions increase with increase in number of windows, damage area and the increase in the number of replaced layers due to moisture damage. With increase in the number of window, damage area and damaged layers, the impact from the replacement module (B4) in the use stage increase whilst the impact from other life cycle stage of wall components remains the same. This is mainly due to the additional impact from the moisture damage and replaced layers. The impact from the window is very significant, even if the potential impact from the window damage is not included in the parametric analysis.

For the parametric analysis where the effect of moisture damage for different number of window, damaged area and replacement of a number of damaged layers considered, the impact from A1-A3 of the wall construction is still the highest (up to 57% for DE, 56% for FR, 54% for SE and 49% for NO wall constructions) followed by replacement (B4) (up to 29% for DE, 24% for NO, 18% for SE and 14% for FR wall constructions). Waste treatment (C3) contributes up to 12% for NO and FR and up to10% for SE wall constructions, whilst the emission from DE wall construction waste treatment is negligible because the German construction does not have membranes as vapour barrier or wind barriers and thus consists of materials that require little waste treatment before reaching the end-of-waste state. The installation module (A5) in the construction process stage contributes for up to 7% of NO, SE and FR and 6% from DE wall constructions. The transport of materials to the construction site (A4) contributes up to 6% for SE, 5% for NO and FR and 3% from DE wall constructions. Deconstruction (C1) contributes up to 4% for SE and FR and 3% for NO and DE wall constructions. Transport to waste treatment contributes up to 1% and insignificant contribution from waste disposal (C4) for all wall constructions.

The impact varies per construction type based on the type of materials used in the wall construction. For example, for the wall construction from DE, the impact from the MDF (third layer) is 55% of the total emission. Thus, replacement of this layer due to the moisture damage further increase the total GHG emission.

3.1.2 Total GHG emissions for different scenarios

The results for different scenarios are presented in Figures 7-10 for closer analysis of the impact from different scenarios considered in this study: area of damage (0 (no damage), 0.687m^2, 1,396m^2, 1,745m^2, 2.6175m^2, 3.49m^2 damaged area), number of window (o (no window), 1, 2 and 3 windows) and damaged layers (0 (no damaged and replaced layer), replacement of 1 layer, 1 &2 layers, 1,2&3 layers, 1,2,3& 4 layers). The results show that GHG emissions significantly increase with increase in the number of windows even for scenarios where no damage area and replaced layers are considered. This is mainly due to the highest GHG emissions contribution from the window compared to the wall components.

The effect from the increase in the damage area become significant with increase in the number of replaced layers. That means the GHG emissions from increase damage area become significant for the case of the replacement of the first three and all four layers compared to the replacement of the first layer and first and second layers. Here it should also be noted that, the type of replaced layer also affect the results as different materials are categorized under the layers based on the impact of the composition of the wall constructions considered in the study (see Table 4).

3.2 Parametric LCA with mould occurrence probability

This part presents the result from probability of failure due to susceptibility to mould growth (section 3.2.1.) and the consequence of probability of failure on total GHG emission (section 3.2.2).

3.2.1 Probability of failure

The cumulative probability distribution plot of the failure event, expressed as mould or decay germination potential, is presented in Figure 11. It is observed that decay never reaches decay rating one in any of the case studies.
Table 5 shows the values of probability of exceeding the mould germination for each of the layers. Different wall constructions show different susceptibility to mould growth depending on the defined mould growth index and the investigated interface. The results of the wall construction from Germany are the most scattered, both relative to the mould growth index and to the interface. Similar behaviour is observed for the wall construction of Norway; however, the influence is mostly affecting the results relative the mould growth index level I. The results of the wall construction from France are highly influenced by the mould growth index level; however, this influence is only affected the results for interface 1 and 2. The opposite is observed for the wall construction from Sweden, where this influence of both the selected mould growth index level or interface is either zero or very insignificant.

In order to evaluate the risk of probability of the failure events on the GHG emission, 4 scenarios have been considered:

- Scenario 1: The probability of failure (mould index I) multiplied with consequence (replacement)
- Scenario 2: The probability of failure (mould index II) multiplied with consequence (replacement)
- Scenario 3: The probability of failure (mould index III) multiplied with consequence (replacement)
- Scenario 4: The probability of failure is not included

3.2.2 Total GHG emissions

In order to evaluate the risk of probability of failure on GHG emission, the values of probability of exceeding the mould growth levels for each of the layers (shown in Table 5) are multiplied with the respective consequences (replacement). The GHG emissions risk are shown in Figures 12-14 for the defined mould index I, II, III, respectively.

As it is observed from Table 5, the results show that the probability of failure is sensitive to the extent of chosen mould index to express the failure event. This influence the risk assessment, where the perturbation derived from the different probabilities of failure for different layers are observed at the corresponding replacement interval (B4) in Figures 11-13. Moreover, the results of the GHG emissions risk show that the parameter considering the number of windows becomes more significant when the acceptance of mould growth level is the highest. The influence of scattered results of the probability of failure (see section 3.2.1) for the wall construction from Germany are also visible in the risk assessment. Lower influence is observed for the wall construction from Norway and France, and almost no influence is observed for the wall construction from Sweden.

For mould index level I, it is noticed that the difference between each layer's probability of failure is relatively significant (Figure 12). This significance decrease for mould index level II (Figure 13). For mould index level III, the graph shows smooth linear behaviour of the risk since the probabilities of failure are very similar for each layer and close to zero (Figure 14).

3.3 Future research perspectives

It should be acknowledged that a number of assumptions have been considered in the development of this parametric LCA tool and the study has highlighted areas that need further work.

3.3.1 Life cycle inventory

In this study, the product stage (A1-A3) GHG emissions data are based on an average Norwegian EPD. The GHG emission results show that the impact from A1-A3 is the most significant. However, this result can also be higher or lower if the material with the highest or lowest GHG emission data is considered rather than the average emission data. This shows the importance of evaluating the type and source of data used during the design phase and considering the environmental performance of the material choice during the construction phase. A sensitivity analysis should be performed using these three alternatives (low, average and high emission data), in order to estimate the level of uncertainty.

The GHG emission from modules in the construction stage (A4-A5), replacement stage (B4) and end-of-life stage (C1-C4) are evaluated based on scenarios developed in the study. Even if emission factors for Modules A4-A5, B1-B7, C1-C4 and D are given in some EPDs, these data cannot be used directly for evaluation of the environmental performance of building or its components, as EPDs are based on one probable scenario, and are not site or context specific. The methodology used in this study is a conservative approach when specific material or suppliers and construction site is not known.

3.3.2 Scenarios

The GHG emission from construction process stage (A4-A5) can be significant for tall buildings. The impact can vary depending on for example means of transport and transport distance used to transport materials and construction workers to construction site, the amount and type of energy use for construction machineries, for heating, cooling, ventilation, drying and lightning during the construction period. Furthermore, the impact can vary depending on different construction methods: from onsite, onsite with prefabricated parts, and entirely prefabricated (offsite) and can also lead to shifting of environmental burdens to another part of the building's lifecycle. Although many LCA studies document GHG emissions from buildings, few focus on A4-A5, and even fewer use detailed life cycle inventory data from the construction site in emission calculations (Wiik et al. 2018). Furthermore, when the construction process stage is included, it typically uses hypothesised data and an incomplete system boundary, which results in a large disparity in embodied GHG emission results from the construction process stage. This can be due to complexity of construction activities, time and cost issues in collecting specific life cycle inventory data directly from the construction site, as well as a lack of good data to make robust estimations of impacts arising from construction site activities. The spike in GHG emissions from the construction process stage raised concern whether new construction can contribute to reaching GHG mitigation goals, no matter how energy efficient buildings are in operation, which result in growing interest in addressing construction GHG emissions (Antti et al. 2012). It would be useful to consider evaluation of the GHG emission from construction process stage of tall wooden buildings using actual data and clear definition of system boundaries in future studies.

The results also show that the impact from the replacement module in the use stage (B4) becomes significant with consideration of different parameters that leads to the replacement of damaged areas and layers. Building components, except for structural components or assemblies that are disruptive to repair or replace, often need maintenance, repair and replacement during the service life of a building (ISO 15686-1 2011). Studies show that the replacement contribute significantly to GHG emissions and the quality of the estimated service life data used may also affect the resulting GHG emissions from different replacement scenarios (Fufa et al. 2017). Consideration of other use stage, such as maintenance (B2) and repair (B3) can further increase this result for tall buildings. Further study is also needed to evaluate the estimated service life of the building materials and the building, which can have a significant impact on the LCA results.

In the end-of-life stage, the common approach that current scenarios are representative for future waste scenarios has considered. However, using the same approach for all means that there at least is a coherent bias. In addition, the generic waste treatment processes in ecoinvent are used in the end-of-life analysis. These processes are to a large extent identical for different materials. The accuracy of this assumption has to be checked in further studies.

3.3.3 Environmental impact indicator

Although several environmental impact indicators are available, this article focuses on the climate change impact based on the quantification of the GHG emissions. Using GWP as a proxy indicator has the benefit of reduced complexity as it is widely accepted indicator among different stakeholders in the building industry, and often correlates with other environmental impacts. From a practical pint of view, comparing different scenarios would become very tedious if different indicators have been used. However, it also risks ignoring important environmental impacts that do not correlate with GWP, such as; toxicity, resource use, and resource depletion (Laurent et al. 2012, Heinonen et al. 2016). This can potentially lead to problem shifting to other impact categories. It is recommended to evaluate this in future studies.

3.3.4 Probabilistic approach

In the parametric analysis, simplified assumptions are used to evaluate the potential effect of moisture damage on the embodied emission of ventilated timber wall constructions. The results from GHG emission show windows are one of the main emission contributor. In this study, the parametric analysis considers only the possible damage related to wall components, excluding the potential impacts of moisture damage of windows on the GHG emissions of wall construction.

The probabilistic assessment can be further developed by considering other sources of uncertainties in the system representation and other types of performances associated to wall constructions. For example, stochastic models of the material properties and geometries or indoor climate can be integrated in the probabilistic methodology. Accurate models are ideally achieved by measurement of the indoor conditions or the materials properties. In addition, this study considered the occurrence of mould and decay as potential failures. However, other types of failure, whose occurrence require mitigation actions, can be included in the methodology to deliver a more overarching consideration of the performance of wall constructions. However, these are recommendations for future research as they fall out of the scope of this study.

3.3.5 Overall

This study can be used to evaluate and minimize the potential GHG emissions of possible moisture damage scenarios on building envelopes. Furthermore, it can enable to consider various improvement measures that reduce the risk, resulting in a robust construction with good function, longer service life and lower embodied GHG emissions during the building's life time. The results show that the background emission data and methodological choices have a significant effect on the GHG emission results. The parametric results are also sensitive to the variables used to estimate the area of replacement, the number of windows, the number of damaged layers and the considered failure event. In addition, the parametric analysis is not tested on case study tall timber buildings. It should be noted that, the tool is not meant to give exact results, rather it can be used for evaluating wall construction schemes and setting moisture performance goals and measures in tall buildings. The tool is also flexible enough to accommodate further developments associated with the improvements or changes of the input variables to consider different scenarios.

4. Conclusions

This article gives an insight into some of the consequences originating from moisture damage have on GHG emissions in timber wall constructions. The results reveal that parametric LCA can be a useful tool for evaluating and minimizing the potential effect of moisture damage around window connections. This enables on the embodied emissions of wall constructions. Performing parametric LCA analysis at early design phase helps to consider alternative design and construction approaches for timber wall constructions that can be used in tall buildings and minimize the potential risks from moisture damage and the associated embodied emissions. In the future, this parametric analysis tool can be used for evaluating wall construction schemes and setting moisture performance goals and measures in tall buildings. Furthermore, there is a room for further development of the tool and change the input variables, background data and type of wall construction in order to evaluate different scenarios and wall construction types that can be used in tall timber buildings.

Acknowledgement

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System boundaries (X=modules included in the study) according EN 15978																			
A1–A3 Product stage			A4–A5 Construction Process stage		B1–B7 Use stage							C1–C4 End-of-life				D1–D4 Benefits and loads beyond the system boundary			
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D1	D2	D3	D4
Raw material supply	Transport	Manufacturing	Transport	Construction installation process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction	Transport	Waste processing	Disposal	Reuse	Recovery	Recycling	Exported energy /potential
X	X	X	X	X				X				X	X	X	X				

Figure 1. System boundaries with respect to life cycle stages covered in the study (EN 15978 2011).

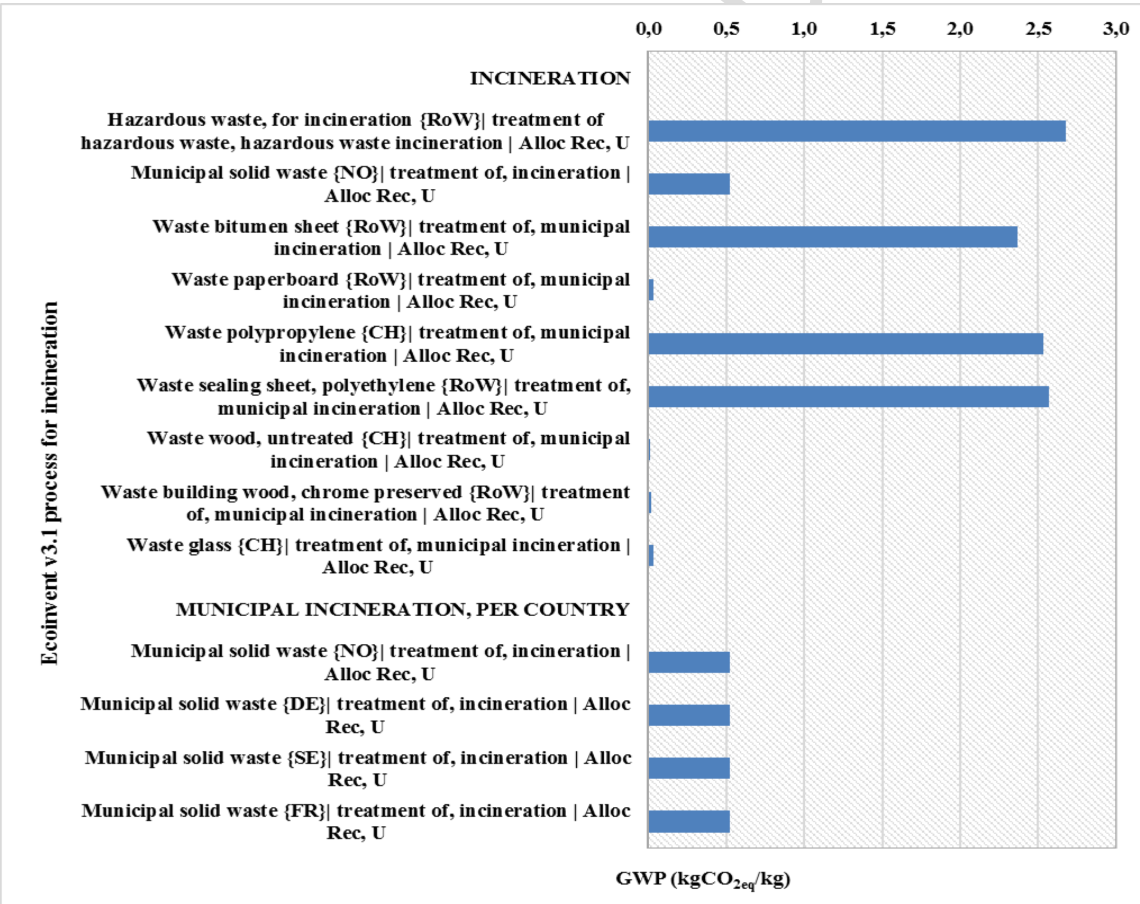


Figure 2. GHG emissions from waste incineration Ecoinvent processes

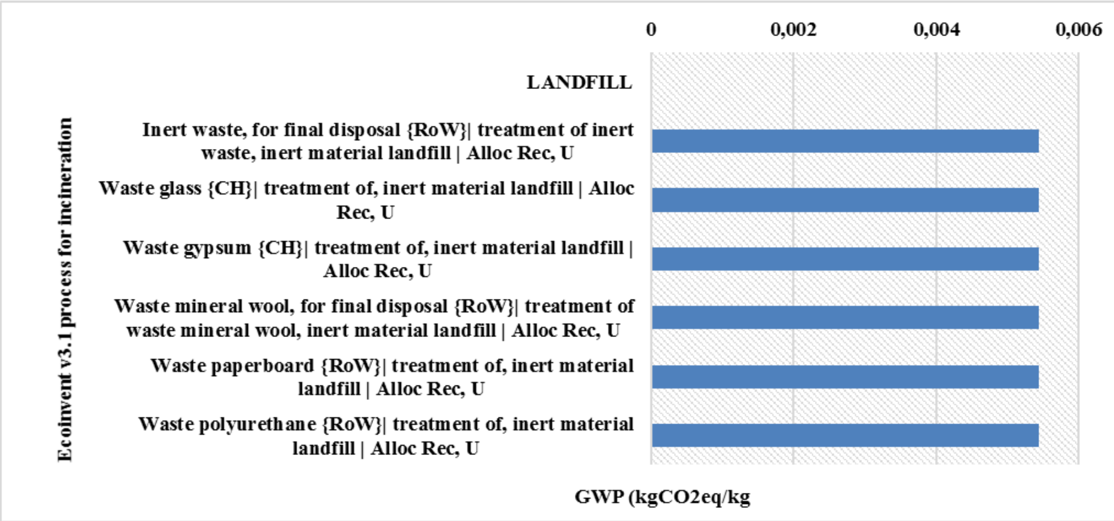


Figure 3. GHG emissions from waste landfill Ecoinvent processes

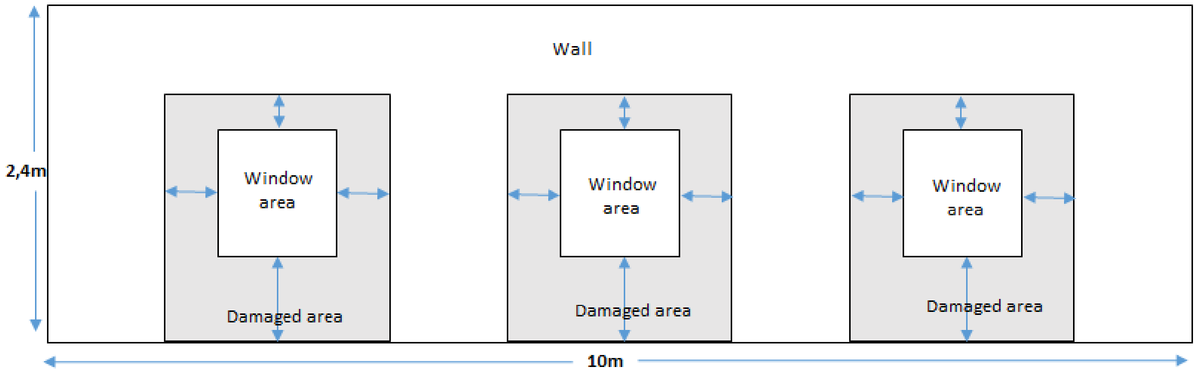


Figure 4. Assumptions taken to calculate the damaged area

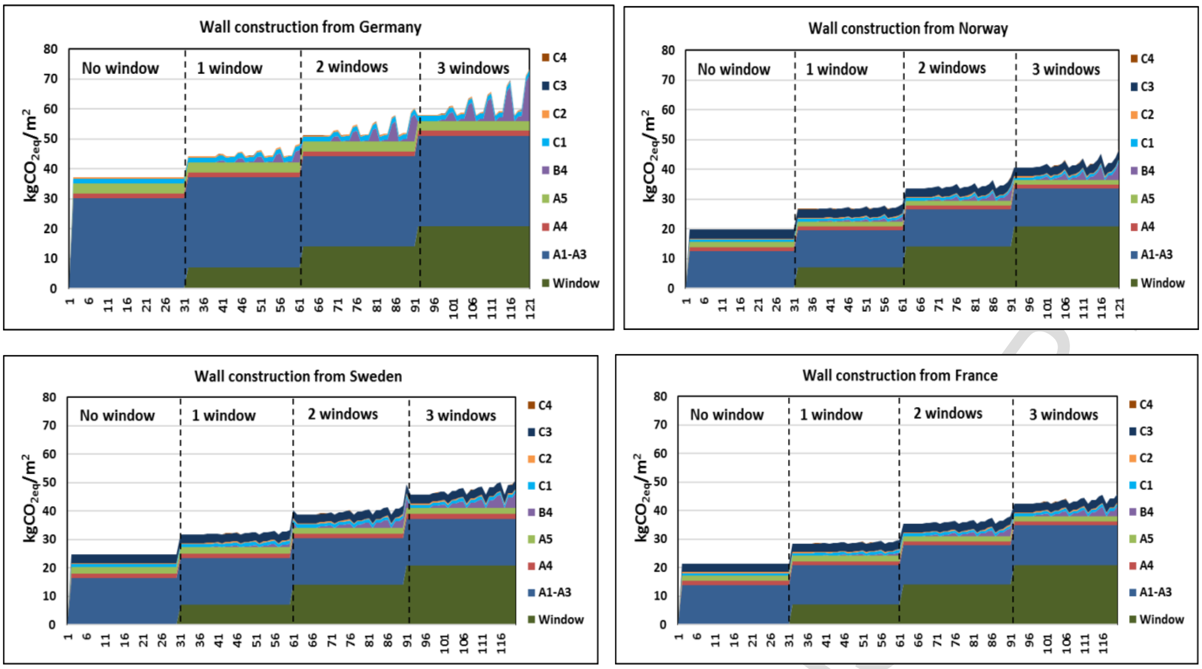
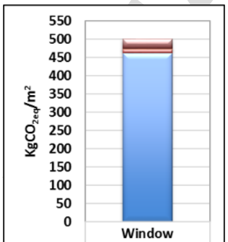


Figure 5. GHG emission per life cycle stages of wall constructions for iterations performed in the parametric analysis for all scenarios (except the probability from mould growth) and total GHG emission from window.



	Window
C4	27,05
C3	0,00
C2	1,74
C1	0,00
B4	0,00
A5	0,00
A4	11,12
A1-A3	462,09

Figure 6. GHG emission per life cycle stage of window.

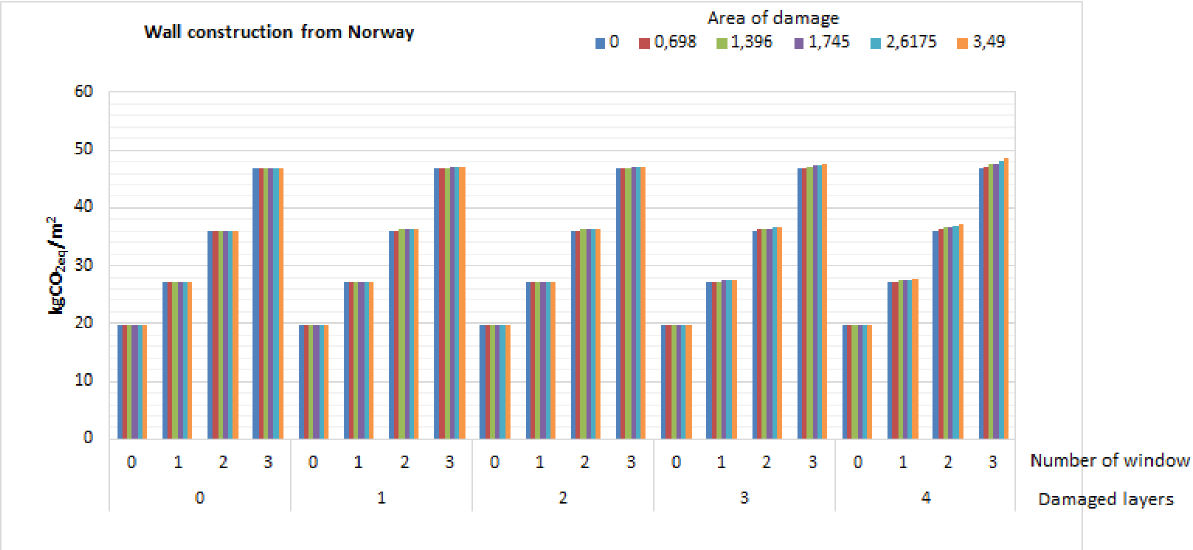


Figure 7. GHG emission per m² of the wall construction from NO for the scenarios considered in the parametric analysis, except the mould probability.

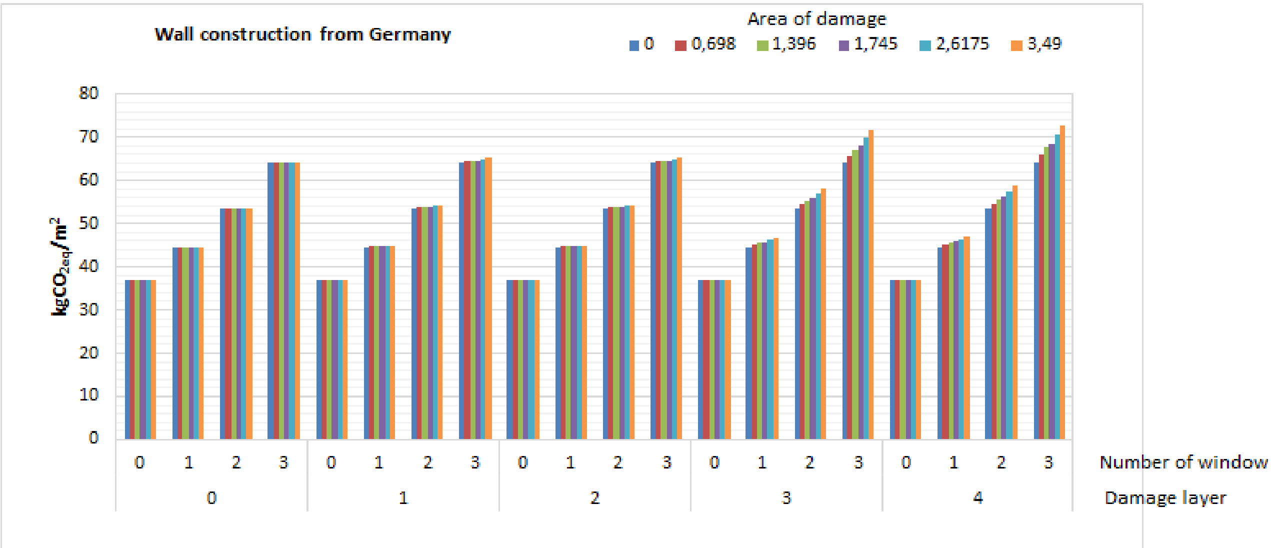


Figure 8. GHG emission per m² of the wall construction from DE for the scenarios considered in the parametric analysis, except the mould probability.

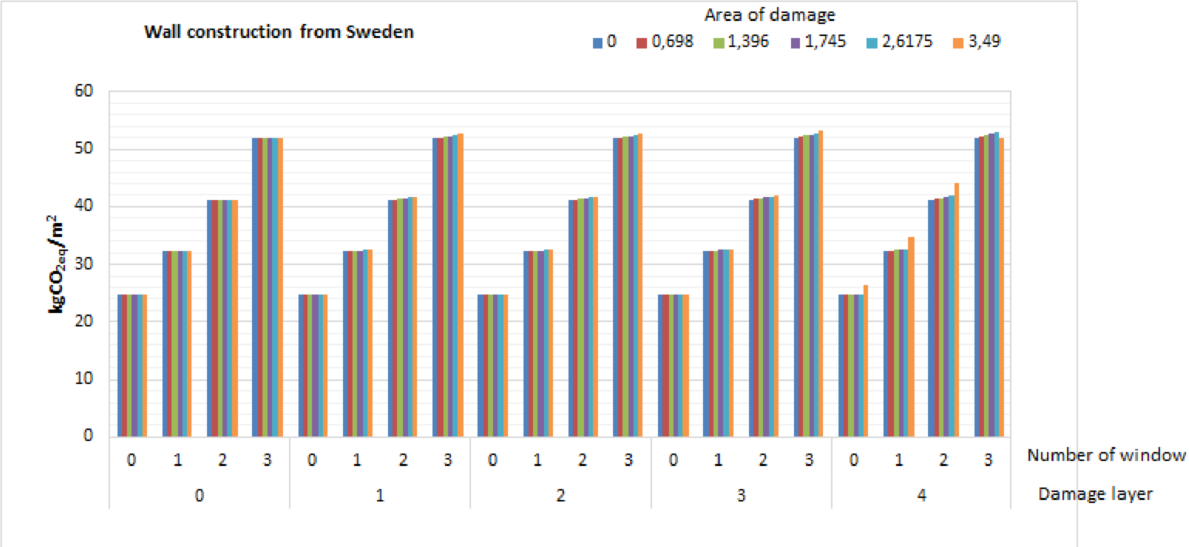


Figure 9. GHG emission per m^2 of the wall construction from SE for the scenarios considered in the parametric analysis, except the mould probability.

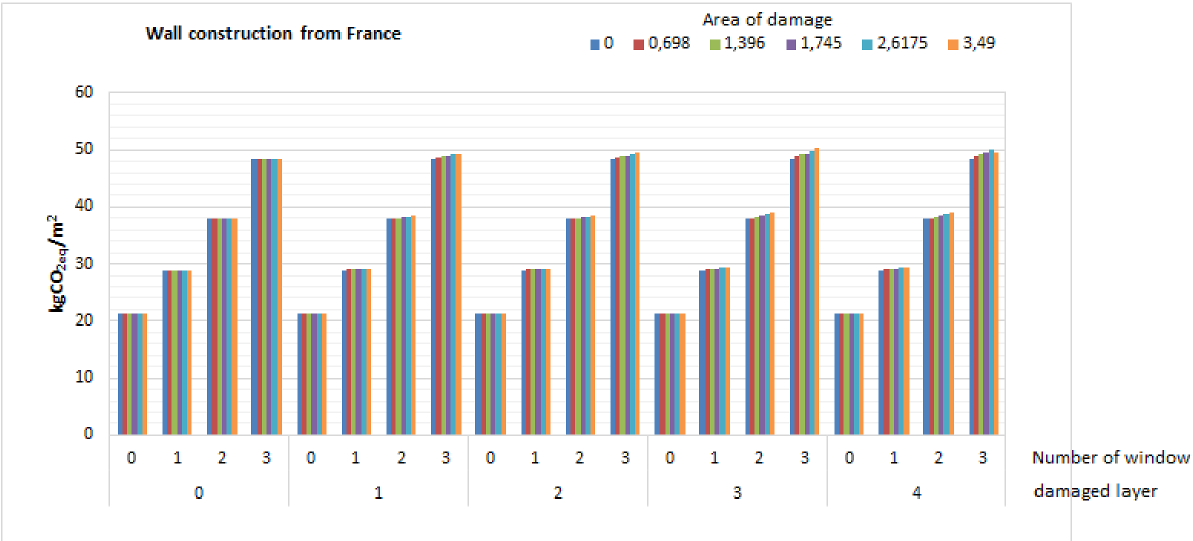


Figure 10. GHG emission per m^2 of the wall construction from FR for the scenarios considered in the parametric analysis, except the mould probability.

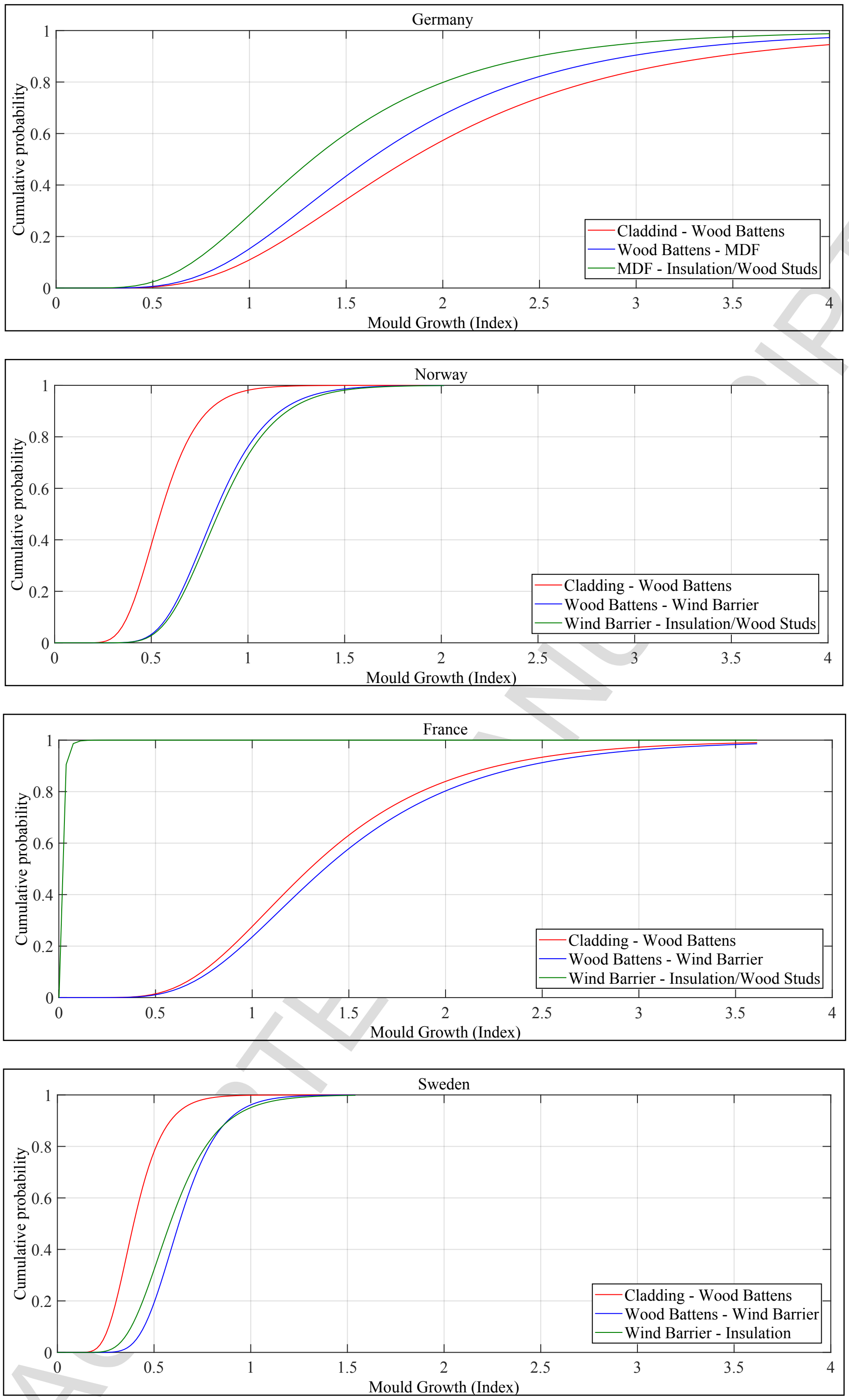


Figure 11. Cumulative probability distribution of mould growth potential in the first three[1] interfaces for France, Sweden, Norway and Germany in 50 years. The definition of the corresponding interface for each construction is explained in Table 5.

[1] The mould growth potential in the fourth interface is always zero.

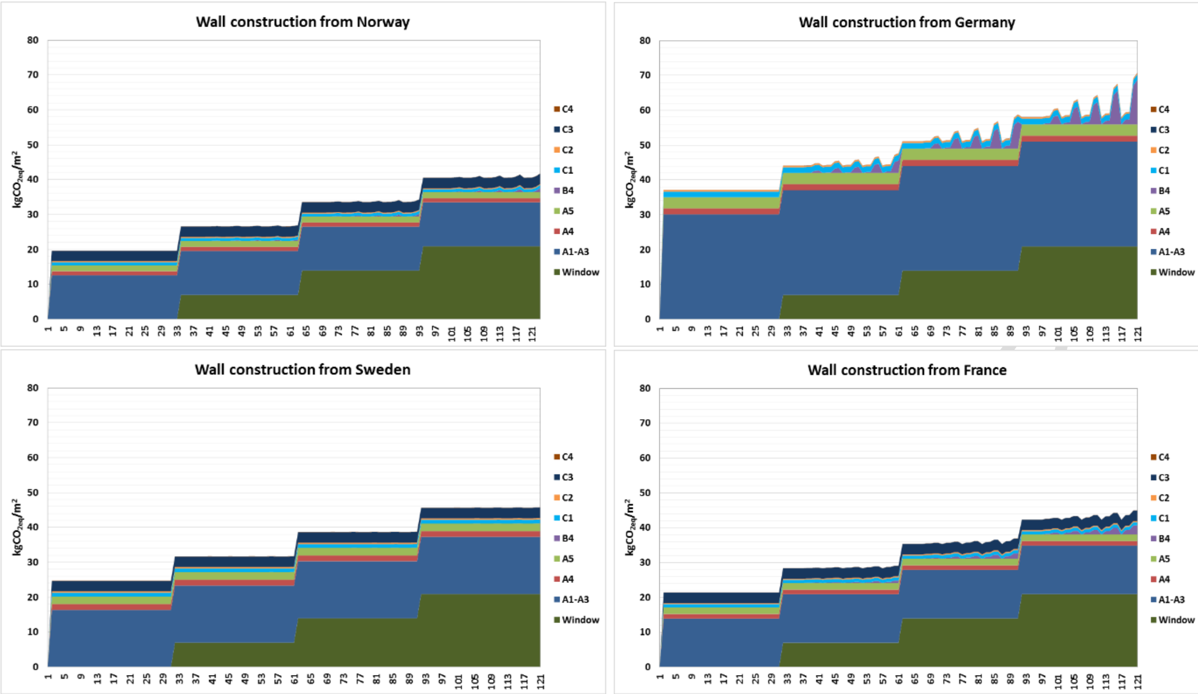


Figure 12. GHG emissions per m² wall construction from NO, DE, SE and FR for iterations performed in the parametric analysis for different scenarios considered in the study, including the risk of probability of failure defined at mould index I.

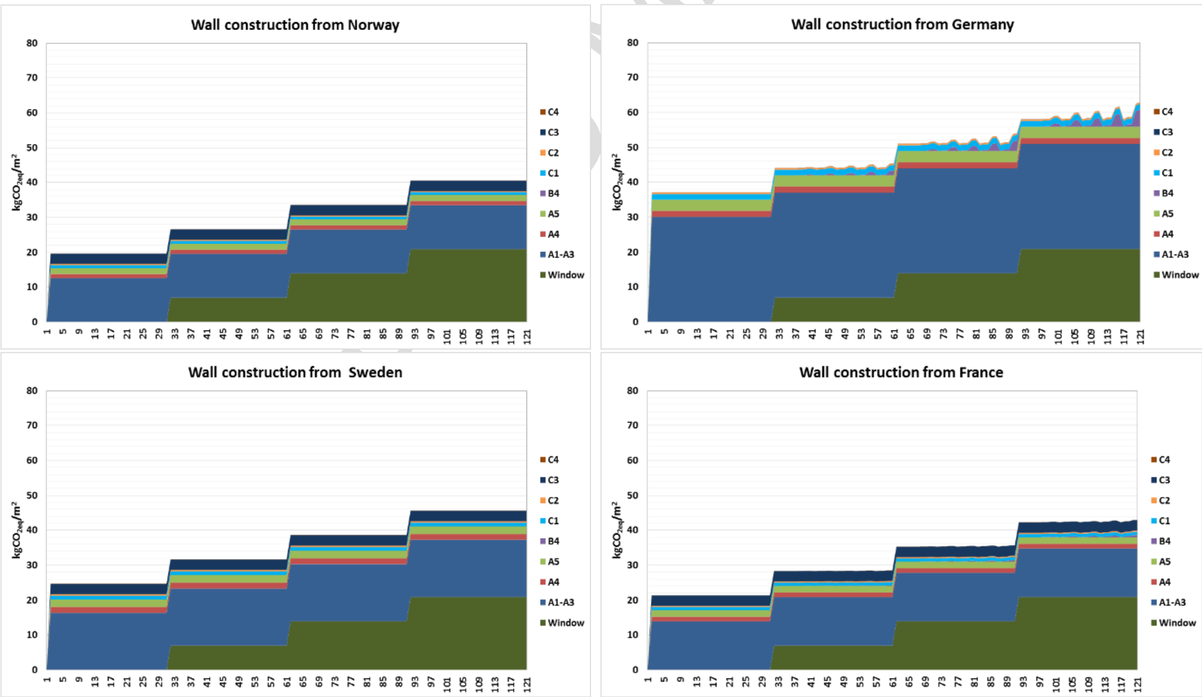


Figure 13. GHG emissions per m² wall construction from NO, DE, SE and FR for iterations performed in the parametric analysis for different scenarios considered in the study, including the risk of probability of failure defined at Mould index II.

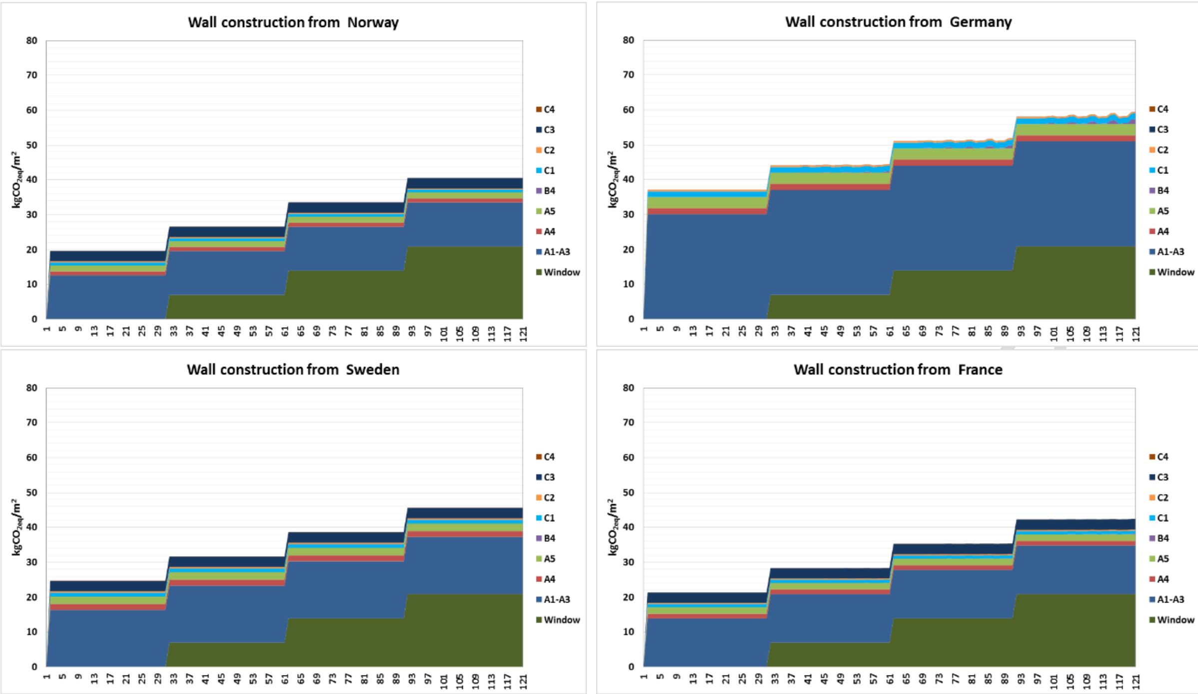


Figure 14. GHG emissions per m^2 wall construction from NO, DE, SE and FR for iterations performed in the parametric analysis for different scenarios considered in the study, including the risk of probability of failure defined at Mould index III.

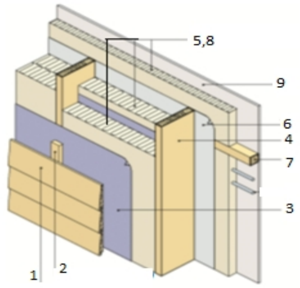
Highlights

- Parametric life cycle assessment is performed to evaluate moisture damage scenarios.
- Probabilistic-based methodology to include risk of mould and decay.
- Wall constructions from four different countries are evaluated.
- The probability of failure is sensitive to unacceptable level of mould growth.
- The parametric results are sensitive to the variables considered.

Table 1. Wall constructions

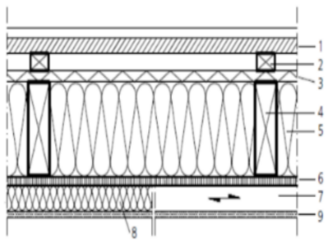
Country	Wall construction	Description

Norway (NO)



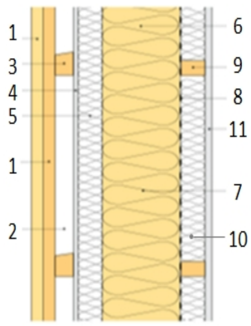
	Material (exterior to interior)	d (mm)	ρ (kg/m³)	Λ [W/mK]	C [J/kgK]	μ [-]
1	Exterior wooden cladding	19	450	0,09	1500	130
2	Wood battens	23	450	0,11	1600	50
3	Wind barrier	0,15	900	0,17	1000	100
4	Wood stud	200	450	0,11	1600	50
5	Insulation (Glass wool)	200	40	0,035	840	1
6	Vapour barrier	0,15	900	0,22	2300	23000
7	Wood battens	48	450	0,11	1600	50
8	Insulation (Glass wool)	50	40	0,035	840	1
9	Gypsum board	12,5	900	0,2	850	10

Germany (DE)



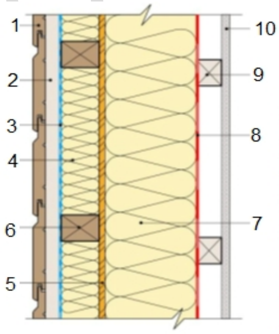
	Material (exterior to interior)	d (mm)	ρ (kg/m³)	Λ [W/mK]	C [J/kgK]	μ [-]
1	Exterior wooden cladding	19	484,51	0,09	1500	130
2	Wood battens	30	484,51	0,11	1600	50
3	MDF	16	737,5	0,1	2000	12
4	Wood stud (spruce)	160	492,92	0,11	1600	50
6	Insulation (Glass wool)	160	46,25	0,035	840	1
7	OSB	15	600	0,13	1500	175
8	Wood battens (spruce)	40	484,51	0,11	1600	50
9	Insulation (Glass wool)	40	46,25	0,035	840	1
10	Gypsum board	12,5	850	0,2	850	10

Sweden (SE)



	Material (exterior to interior)	d (mm)	ρ (kg/m³)	Λ [W/mK]	C [J/kgK]	μ [-]
1	Exterior wooden cladding	44	430	0,09	1500	130
3	Wood battens	34	430	0,11	1600	50
4	Wind barrier	0,2				
5	Insulation (Glass wool)	70	19	0,035	840	1
6	Wood stud (spruce)	195	430	0,11	1600	50
7	Insulation (Glass wool)	195	19	0,035	840	1
8	Vapour barrier	0,2		0,22	2300	23000
9	Wood stud	45	430	0,11	1600	50
10	Insulation (glass wool)	45	19	0,035	840	1
11	Gypsum board	12,5	720	0,2	850	10

France (FR)



	Material (exterior to interior)	d (mm)	ρ (kg/m³)	Λ [W/mK]	C [J/kgK]	μ [-]
1	Exterior wooden cladding	22	455	0,09	1500	130
2	Wind barrier	0,5	1100	0,17	1000	70
3	Insulation (Glass wool)	60	21	0,035	840	1
4	OSB	10	615	0,13	1500	139
5	Wood stud (spruce)	145	450	0,11	1600	50
6	Insulation (Glass wool)	145	40	0,035	840	1
7	Vapour barrier	0,5	900	0,22	1800	10000
8	Wood battens	48	450	0,11	1600	50

	(spruce)						
9	Gypsum board	13	900	0,2	850	10	

Table 2. List of A1-A3 data sources and emission factors used for parametric LCA

Materials	Average weight (kg)	Average emission factor from A1-A3	No. of EPDs	EPD selection criteria	References
Exterior wooden cladding	10.70	1.88 $kgCO_{2eq}/m^2$	7	EPDs for treated wooden cladding, excluding biogenic carbon	NEPD 00243N; NEPD-473-330-EN; NEPD-310-180-NO; NEPD-378-264-NO; NEPD-474-330-NO; NEPD 00294N; NEPD-472-330-NO
Wood battens	450.00	43.00 $kgCO_{2eq}/m^3$	1	Relevant EPDs, excluding biogenic carbon	NEPD-307-179-EN
Medium-density fibreboard (MDF)	7.68	11.80 $kgCO_{2eq}/m^3$	1		NEPD-1326-428-NO
Wood stud	420.00	53.00 $kgCO_{2eq}/m^3$	1		NEPD-308-179-EN
Wind barrier (Polypropylene)	0.50	1.08 $kgCO_{2eq}/m^2$	2	Relevant EPDs	NEPD-260-NO; NEPD-207-260-NO
Insulation (Glass wool)	0.61	0.73 $kgCO_{2eq}/m^2$	2		NEPD 221E rev2; NEPD 00244E
Vapour barrier (Polyethylene foil)	0.14	0.37 $kgCO_{2eq}/m^2$	3		NEPD 00273N; NEPD-341-20-NO; NEPD-1230-387-EN
Oriented Strand Board (OSB)	617.00	215.00 $kgCO_{2eq}/m^3$	1	EPD from IBU (due to lack of EPD from EPD Norway), excluding biogenic carbon	EPD-KRO-20150067-IBD2-EN
Interior cladding (gypsum board)	9.91	3.02 $kgCO_{2eq}/m^2$	13	EPDs for 12.5 ± 0.5mm, excluding biogenic carbon	NEPD-1260-406-EN; NEPD-1265-407-EN; NEPD-354-246-EN; NEPD-356-246-EN; NEPD-358-246-EN; NEPD-413-292-EN; NEPD-417-293-EN; NEPD-416-293-EN; NEPD- 415-292-EN; NEPD-414-292-EN; NEPD-412-292-EN; NEPD-110-177-EN; NEPD-113-177-EN
Window	64.02	154.03 $kgCO_{2eq}$/window	7	EPDs for window with aluminium cladding, excluding biogenic carbon	NEPD 00233E; NEPD 00242E; NEPD-329-212-NO; NEPD00245E; NEPD00256E; NEPD00176E; NEPD-384-265-NO; NEPD-385-265-NO; NEPD00174E

Table 3. Description of parameters

Parameters	Variables	No. of variables	Main assumptions used	Cross reference
Number of window	0; 1; 2; 3	4	- Area of reference wall=24 m^2; - Area of window=1.82 m^2; - Window to wall ration =22%	Chapter 2.4.1
Area of replacement (m^2)	0; 0,70; 1,40; 1,75; 2,62; 3,49	6	- Damaged area around the window=100% damaged wall area below the window, 50% damaged wall area on the two sides of the window and 20% damaged wall area on the top of the window - Percentage of extent of replacement= 20%,40%, 50%, 75% and 100%	Chapter 2.4.2
No of damaged layers	0; 1; 2; 3; 4	5	- Replacement of the first 4 damaged layers	Chapter 2.4.3
Total number of unique scenarios		120		

Table 4. Wall construction layers considered in the parametric analysis

Layer	**Norway**	**Germany**	**France**	**Sweden**
1	Exterior cladding	Exterior cladding	Exterior cladding	External cladding
2	Wood battens	Wood battens	Wind barrier	Wood batten
3	Wind barrier	MDF	Insulation	Wind barrier
4	Wood stud*	Wood stud*	OSB	Insulation
5	Insulation	Insulation	Wood stud*	Wood stud*
6	Vapour barrier*	OSB*	Insulation*	Insulation*

*Layers assumed not to replaced and not considered in the parametric analysis

Table 5. The probability of non-exceedance a given mould growth index in the first four interfaces for each country in 50 years.

Country	**Mould Index**	**Interface 1**	**Interface 2**	**Interface 3**
Norway		Cladding - Wood Battens	Wood Battens - Wind Barrier	Wind Barrier - Insulation/Wood Studs
	I	0,980	0,761	0,728
	II	1	0,999	0,999
	III	1	1	1
Sweden		Cladding - Wood Battens	Wood Battens - Wind Barrier	Wind Barrier - Insulation
	I	0,998	0,96118	0,950
	II	1	1	1
	III	1	1	1
Germany		Cladding - Wood Battens	Wood Battens - MDF	MDF - Insulation/Wood Studs
	I	0,109	0,152	0,283
	II	0,573	0,672	0,798
	III	0,844	0,904	0,951
France		Cladding - Wood Battens	Wood Battens - Wind Barrier	Wind Barrier - Insulation/Wood Studs
	I	0,276	0,235	1
	II	0,839	0,802	1
	III	0,972	0,961	1