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# Footprints of failure: Quantifying carbon impacts of roof leakages in a single-family residential building

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**Abstract.** To meet the UN Sustainable Development Goals of climate change mitigation and sustainable cities, low-carbon or carbon-negative buildings are becoming increasingly common. The buildings are planned to compensate for the embodied energy in their materials by using low-emission materials and generating emission-free energy. Embodied energy is minimized while energy generation is maximized. However, embodied energy calculations seldom consider the risk of building defects that require repairs or early replacement of building elements. As such, a building's sustainability is often calculated under the assumption that significant defects do not happen, which is known to rarely be the case. In this article, the material and monetary costs of repairing building defects are analysed. Findings suggest that certain building defects, like major roof leaks, have a significant carbon footprint. A large portion of this footprint can be attributed to the drying of the building after a leak is discovered. Building defects are common enough that the risk should not be neglected in life cycle analyses. Likewise, measures taken to reduce the risk of building defects, such as avoiding design solutions known to pose difficulties, may be considered as means to improve the sustainability of a building as well as reducing economic costs.

## 1. Introduction

The Sustainable Development Goals (SDGs) presented by the United Nations lay out a vision of a future of sustainable human development. The goals are formulated in the 2030 Agenda for Sustainable Development, eclipsing matters such as gender equality, poverty elimination, access to sanitation, and sustainable cities [1]. The 17 goals are further divided into 169 targets. The building sector will play a crucial role in fulfilling several of these targets.

This article will primarily concern issues relevant to targets 9.4, 12.2 and 12.5, which address sustainable use of natural resources and the reduction of waste. It has already become a trend in the building sector to design buildings using significantly fewer resources and requiring less energy to operate than the norm only a few decades ago. So-called “zero emission buildings” aim to create buildings that fully or partially compensate for the resources used in their construction and operation through renewable energy generation [2].

However, experience shows that buildings do not always perform as intended. For various reasons, defects occur which require repairs or replacement of building elements. Defects such as roof leakages can inflict serious damage to buildings in a relatively short time span [3]. Restoring the functionality of the building element will incur costs of time and money, as well as several types of emissions. However, costs will also occur if the functionality is not restored, i.e. through reduced occupant comfort, increased



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energy use, and lower building value. Building defects present the stakeholders with a lose-lose situation, and it is evident that preventing defects from occurring is vastly preferable over repairing or accepting them. This paper examines the environmental impact of building defects through the following research questions:

- What are typical defects requiring repair/replacement in modern low-energy buildings?
- What are the costs of fixing these defects in terms of carbon emissions?
- What implications do these costs carry for the achievement of sustainable net-zero-energy buildings?

The article will examine a case building through three defect cases, listing the materials needing to be replaced in each case. The cases are constructed around a typical Norwegian residential building, whose materials are examined through their Environmental Product Declarations (EPDs).

## 2. Theoretical background

### 2.1. Sustainable Development Goals

The UN Sustainable Development Goals (SDGs) can be used as a framework showing how various sectors of society may change to create a sustainable future. For the building sector, goals related to smart cities and resource consumption are the most relevant. The building sector is already working towards increased sustainability, with certifications such as LEED or BREEAM becoming increasingly common, and energy requirements in technical regulations being ever stricter.

An often-overlooked aspect of building sustainability is the need for high quality. Even the most sustainably designed building may have an enormous climate footprint if elements must be replaced due to premature deterioration. Sustainable consumption in the building sector is not just about creating the least resource-intensive buildings possible, but also to build them in such a way that frequent repairs will not be necessary.

### 2.2. Building defects

A building defect is defined by [4] as “[when] a component has a shortcoming and no longer fulfils its intended function.” A study by [5] found that in Victoria, Australia, costs associated with building defects represented 4% of the contract value of new dwellings/renovations. Nielsen [6] estimated that the annual cost of defects represented 10% of the Danish construction sector’s turnover. Schultz et al. [7] list several other estimates of the magnitude of costs of rework, most of them finding the extra costs of defects to be between 2.4 and 12 % of the costs of a project.

However, while estimating the magnitude of building defect costs, all the authors cited above all highlight some level of difficulty obtaining comprehensive data on building defects. Databases of building defect cases are usually created by actors for cases they themselves have been involved with, and there appears to be a general reluctance to share data [4]. Studies on building defects have generally pulled data from a database made accessible to the authors [5,8–11], mapped common defects through questionnaires/interviews with actors in the building sector [12,13], or a combination of the two [7]. As remarked in a review by Yung and Yip [14], this pervasive lack of comprehensive data often causes inadequate sample size to be an issue in studies on building defects.

These identified literature on building defects all consider the issue from an economical perspective. The authors have not been able to find research data on the environmental costs of building defects.

### 2.3. Roof defects

Some typical building defects can nonetheless be identified. Gullbrekken et al. [10] examined roof defects in Norwegian residential buildings and found that damages were primarily caused by precipitation moisture in 49 % of all identified cases, out of 465 roof cases dating between 1993 and 2002. In compact roofs, 73 % of all defect cases were caused by precipitation or condensation of indoor moisture. In 2017, 45,000 cases of moisture damage were registered in Norway, only around half of

which were related to plumbing [15]. A conservative estimate for leaks and condensations in Norway would be around 10,000 cases annually.

Moisture accumulation may compromise the thermal properties of insulation materials, cause corrosion in metallic materials, and facilitate the growth of fungus. In wooden structures, moisture accumulation is particularly dangerous because it deteriorates the load-bearing structure. As moisture damages caused by leaks in the building envelope account for such a large portion of building defect cases, this article will be using moisture leak scenarios as the basis for its study cases.

Flat, compact roofs help reduce building heights compared to sloped roofs, and allow full-height, level ceilings over the entire top floor, but are associated with certain building technical challenges [16]. As compact roofs consist of multiple watertight layers, the drying capacity of such roofs is low, and moisture may propagate slowly through the structure for years before a leak is eventually discovered.

#### *2.4. EPDs and embodied energy*

The term “embodied energy” refers to the energy used for the creation, maintenance and disposal of an item. Embodied energy may be calculated for the entire lifetime of the item, or parts of it (raw materials, manufacture, transport, disposal, etc.). Similarly, the carbon footprint of an item is the equivalent CO<sub>2</sub> emissions incurred over the various phases of the item’s lifetime. Other environmental footprints, such as water use and ozone depletion, may also be counted and calculated in a life cycle analysis (LCA). Manufacturers may opt to document and declare the environmental footprints of their products in a document known as an Environmental Product Declaration (EPD). EPDs need to conform to the standard ISO 14025:2006 [17].

An EPD lists the environmental impacts of their product over various stages of the product’s lifetime, namely manufacturing and installation (A), use (B), End of life (C) and beyond-lifetime (D). Each stage is divided into several modules, such as transport of raw materials from factory and transport of finished products (A2 and A4, respectively). In this article, stages A and C will receive the most focus, as it presumes defect cases discovered and repaired before any use-related impacts are incurred. Additionally, several of the EPDs do not declare emissions from stage B, making its inclusion in the calculations impractical.

### **3. Method**

A pre-fabricated house design was used as a basis for the research, as a full set of schematics of the building were available to the authors. Typical building damages were selected for investigation based on the authors’ experience and available building defect statistics. Declared data from EPDs were then used to determine the environmental footprint of replacing the materials damaged by the defect. The Global Warming Potential (GWP, equivalent-CO<sub>2</sub> emissions, termed kg CO<sub>2eq</sub>) of the materials were summed up to find the total carbon footprint of the three defect cases.

#### *3.1. The case building*

The case building is a pre-designed house model called Trend 2 [18]. The model is designed as a row house but may also be built as a standalone dwelling. In the Norwegian residential building stock, detached houses and row houses make up the majority of residential buildings [19]. The building is built with a flat, compact roof, which is somewhat uncommon for standalone dwellings but popular in the “funkis” (functionalism) style of architecture, and also widely used for larger apartment buildings. As the Norwegian building code requires the same level of insulation in buildings all over the country, the Trend 2 dwelling can be assumed representative for single-family dwellings all over Norway for the purpose of material study. It is typical both in terms of size, architectural solutions, technical solutions, and material selection.

Trend 2 has a footprint of 64.7 square meters and a heated floor space of 129.4 square meters. The roof construction consists (from the top down) of a roofing membrane, 250 mm insulation, a particle board, a vapour barrier made from 0.15 mm polyethylene, ceiling beams with dimensions 48 x 198 mm,

and a ceiling board. A life cycle impact analysis of the Trend 2 model estimated the total embodied emissions of the building to be equivalent to 25,176 kg CO<sub>2eq</sub> [20].

### 3.2. Materials

The available schematics of the Trend 2 model dwelling did not specify which products were to be used in the construction. As such, assumptions had to be made based on a selection of available products on the market. Environmental Product Declarations (EPDs) for the materials were gathered using the database of the Norwegian EPD foundation [21]. The declared global warming potential per unit of each product was added up for production steps A1-A5 (raw materials, transport to manufacturing, manufacturing, transport to site, and construction installation).

Additionally, severe moisture damages may require industrial dehumidifiers to dry the building to prevent rot. It is assumed that an electric heater drawing 10 kW of power from the electric grid would be required to dry the building after a severe leakage. The Nordic electricity mix is estimated to have an average GWP of 0.136 kg CO<sub>2eq</sub> /kWh [22].

The products used in the roof construction of the case building, and the specified amounts required to construct 1 m<sup>2</sup> of the roof, are listed in

Table 1.

Table 1: Products and amounts used in the construction of the roof of the case building. The amount of each material required to manufacture and dispose of 1 m<sup>2</sup> of roof construction is specified, noted by system borders A1-A5 and C1-C4 respectively. Note that wood materials have a net negative Global Warming Potential in the manufacturing phase, as carbon is absorbed from the atmosphere to grow a tree. The carbon is released again when the wood decomposes.

Building element	Product	Declared Unit (DU)	Amount per unit* of the roof	Kg CO <sub>2eq</sub> /unit (A1-A5)	Kg CO <sub>2eq</sub> /unit (C1-C4)	Reference (EPD)
Roofing membrane	Protan SE 1.6 Roofing Membrane	1 m <sup>2</sup>	1 layer	4.41E+00	2.43E-01	[23]
Insulation	Glava Glass Wool Proff 34	1 m <sup>2</sup> x 34 mm	250 mm (factor 7.6)	3.69E+00	3.47E-02	[24]
Vapour barrier	Gram vapour barrier	1 m <sup>2</sup>	1 layer	3.39E-01	3.89E-01	[25]
Particle board	Forestia particle-board	1 m <sup>3</sup>	18 mm board (factor 0.018)	-1.44E+01	1.98E+01	[26]
Ceiling boards	Arbor painted particle-board	1 m <sup>2</sup>	1 layer	-6.11E+00	1.39E+01	[27]
Ceiling beams	Moelven S-bjelke (glulam beam) 48x300 mm	1 m <sup>3</sup>	1 m 48x300 mm beam (factor 0.0144)	-8.59E+00 (per m beam)	1.01E+01 (per m beam)	[28]
Electricity (for dehumidifier)	Nordic electricity mix	1 kWh	10 kW	1.20E+00 (per hour)	-	[22]

\*The unit is m<sup>2</sup> unless otherwise specified, such as for the ceiling beams.

### 3.3. Damage cases:

Three damage scenarios were evaluated, all assuming the same initial defect, but differing in magnitude and duration before the defect is discovered. It is presumed that all materials are swapped like-for-like in the repair process, and that the existing materials are so damaged they cannot be reused.

#### 3.3.1. Case 1:

A simple perforation of the roofing is discovered quickly after installation. Water does not penetrate far into the insulation below, and the defect is repaired by tearing off 1 m<sup>2</sup> of roofing and leaving it to dry for a day before new roofing is applied over the hole. The case requires replacement of 1 m<sup>2</sup> of roofing and running the dehumidifier for 24 hours, drawing 240 kWh of electricity from the grid.

#### 3.3.2. Case 2:

Leaks in the roofing are discovered a couple of years after building handover. Water has penetrated into the insulation and soaked it to the point of needing replacement. However, the load-bearing structure of the roof is not damaged, as the water has not infiltrated beyond the vapour barrier. The case requires replacement of 10 m<sup>2</sup> of roofing and insulation, but not the vapour barrier or layers below. Drying the roof requires running the dehumidifier for 14 days (336 hours – 3360 kWh).

#### 3.3.3. Case 3:

Major leaks in the roofing are discovered several years after building handover. The insulation of the roof is damaged to such a degree it becomes necessary to tear out and rebuild the entire roof, including the sheathing and internal ceiling boards. Additionally, a couple of roof beams are so damaged by fungus in places, it is decided to replace them entirely. The case requires a complete replacement of the entire roof (64.7 square meters of every layer) and 20 meters of ceiling beams (which will have to be replaced in their entirety even if only parts are damaged). Note that similar damages may also occur from condensation of indoor moisture penetrating the vapour barrier [3]. To dry the building, the dehumidifier needs to run for 60 days (1440 hours – 14400 kWh).

## 4. Results

The resulting equivalent carbon emissions of the three defect cases are summed up in Table 2. Note how, for the minor and medium defect cases, the carbon emissions associated with the dehumidifier are vastly larger than for the materials. Even in the major defect case, the carbon impact of the dehumidifier exceeds that of the disposal and replacement of materials.

Table 2: Embodied CO<sub>2</sub> emissions associated with the disposal and replacement of materials in the three defect cases, and of the electricity required to dry the building.

Case	1: Minor defect	2: Moderate defect	3: Major defect
GWP of materials [kg CO <sub>2eq.</sub> ]	4.66	83.8	1475.57
GWP of drying [kg CO <sub>2eq.</sub> ]	31.68	443.52	1900.80
Total GWP [kg CO <sub>2eq.</sub> ]	36.34	572.32	3376.37

The total embodied carbon emissions of the building is estimated to be slightly above 25,000 kg [20]. The moderate defect case incurs carbon emissions around 2 % of this, most of which is attributed to building drying. Note that this number is very sensitive to the energy source in question, as well as the power drawn by the dehumidifier.

## 5. Discussion

This paper investigated the following research questions: What are typical defects requiring repair/replacement in modern low-energy buildings, what are the costs of fixing these defects in terms of carbon emissions, and what implications do these costs carry for the achievement of sustainable net-zero-energy buildings?

Available scientific literature suggests a lack of comprehensive data on building defects, as existing databases tend to be created for internal use by single actors and are based on data reported solely by the actor in question. Comprehensive databases listing all building defects within a geographical area/region are generally not available. However, it is known that moisture accumulation from precipitation is a crucial factor in building damage in a Norwegian context, so it was chosen to base the defect scenarios on leaks in a compact roof.

For small damage cases, the cost of drying the building after a moisture leak appears to be the dominant contribution to the carbon footprint of a defect case, owing to the large amount of energy required – several kilowatts of continuous power for days or weeks on end. Note that using electricity to run the dehumidifier reduces the environmental footprint tremendously compared to using fossil fuels, owing to the large share of renewable electricity sources in the Nordic power grid. Only for significant damage cases requiring the replacement of large amounts of material does the embodied energy of the materials become a dominant factor. These numbers are of course susceptible to change in regions with a more carbon-heavy electricity mix or when using materials with a larger carbon footprint. The emissions will also depend heavily on the power drawn by the dehumidifier as well as the duration it is running. However, the research shows emissions related to drying will be significant in any case, as the power draw will be in the range of several kilowatts and the duration will be in the range of days to weeks.

Data from the Norwegian insurance industry suggests around 20,000 cases of moisture damage excluding leaks from pipes occur in Norwegian residences annually [15]. The results of this research imply the carbon impact of these moisture damages to be any between 600 and 60,000 tons of CO<sub>2</sub> each year.

The calculations suggest that the carbon footprint of a building defect may grow a hundredfold if the defect goes unnoticed for long enough. The economical cost of a defect left unattended is presumed to escalate in a similar fashion. An undetected defect may not only be costly to the building owner, but also represent a significant carbon footprint. It follows that a truly sustainable solution does not only have a small environmental footprint during construction and regular operations, but also in cases where repair or replacement is necessary. For instance, reducing the time it takes to dry out moisture may drastically reduce the carbon footprint of minor defects. Additionally, thorough inspections at regular intervals during the operations phase may detect defects at an early stage, drastically reducing the risk of major defect scenarios and subsequently the potential environmental footprint of defects.

## 6. Conclusions

The research uses data from EPDs and three constructed defect cases to estimate the carbon footprint of a minor, moderate and major roof defect in the context of a Norwegian detached dwelling. The results show that the disposal and replacement of materials incurs minor carbon emissions for minor and moderate defect scenarios, but that removing moisture from the damage building has significant associated carbon emissions. For major defect cases, material-related emissions eventually overtake those related to drying, but the latter continues to be a major contribution to the total global warming potential of the scenario. It follows that a reduction in the time it takes to dry the structure might lead to a significant reduction in the building's carbon footprint, should a leak scenario occur.

The prospect of major roof leaks should influence the design process of sustainable buildings. A solution with low emissions in the construction and operations phase might not be ideal if it turns out to be complicated to repair and difficult to dry. The repair process of a defect may hide significant carbon footprints that may be avoidable by quality control in the construction phase, continuous inspections throughout the operations phase, or conscious design that takes defect scenarios into account.

Due to uncertain statistics, determining the exact impact of carbon emissions from building defects is a challenging task. Nevertheless, it can be readily assumed that the magnitude of these emissions is significant. More thorough charting of building defects will be needed to determine the impacts with greater accuracy.

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