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Erlend Andenæs

Risk assessment of blue-green roofs

Doctoral thesis

NTNU
Norwegian University of Science and Technology
Thesis for the Degree of
Philosophiae Doctor
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Department of Civil and Environmental
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… but there's no sense crying

over every mistake

You just keep on trying

till you run out of cake …

– GLaDOS[1]

[1] Coulton, Jonathan. *The Orange Box* video game soundtrack. Valve Corporation, 2007.

Preface

This PhD has been completed at the Department of Civil and Environmental Engineering, which is part of the Faculty of Engineering at the Norwegian University of Science and Technology (NTNU). It is written as part of the research project *Klima 2050*, a centre for research-based innovation (SFI). The aim of Klima 2050 is to reduce the societal risks associated with climate change, increased precipitation, and flood water exposure within the built environment.

The PhD project's main supervisor has been Professor Tore Kvande at NTNU. Dr.ing. Berit Time, Chief Scientist at SINTEF Community, and Professor Tone Muthanna at NTNU have served as co-supervisors.

The thesis investigates building quality risks associated with the design, construction, and operation of blue-green roofs. Blue-green roofs are vegetated roofs built to aid stormwater management in urban areas by delaying and retaining rainwater runoff on rooftops. Parts of the work have been carried out in cooperation with partners in the Klima 2050 consortium.

SFI Klima 2050 is funded by the Research Council of Norway (grant number 237859) and the consortium partners.

More information about the research project can be found at www.klima2050.no

June 2021

Erlend Andenæs

Acknowledgements

It is said that it takes a village to raise a child. Likewise, it takes an office landscape to complete a PhD. I have been fortunate to work in a very supportive environment. While this thesis has my name on the cover, it certainly could not have been completed in its current form without the combined effort of more people than I could possibly hope to name here. First, I would like to extend my sincerest thanks to my supervisors. Thank you to Tore Kvande for always keeping up to date with my doings, and for helping me do everything better. As my main supervisor, he has followed my work closely and helped me stay on track throughout the duration of the PhD. Many thanks to Berit Time for invaluable input, help, research design and for keeping the whole project run smoothly. I gratefully thank Tone Muthanna for expertise and insight in a field I've only barely scraped the surface of.

Other people involved in the project deserve a mention as well. Jardar Lohne has been of invaluable help during the writing processes, and for helping to ask, "what does that mean?" as many times as necessary. Atle Engebø has been a great resource and co-author whenever the subject moved on towards project management. Olav Torp has helped me make sense of what risk is all about. Graphical designer Remy Eik-Nikolaisen in SINTEF has greatly lifted the quality of the work through excellently drawn figures and illustrations. A thanks to Lars Egner at NTNU's department of psychology for helping to understand the small yet crucial piece of cognitive science included in the thesis.

I have also received great help from partners in Klima 2050. Special thanks to Ole Mangor-Jensen and Tuva Lien at Skanska, Håkon Einstabland at Statsbygg, and Per Møller Pedersen at Storm Aqua. Their input has been extremely helpful for understanding the perspectives of industry actors. The work of Petter Martin Skjeldrum at Multiconsult has been of great inspiration for my thesis.

This section would not be complete without an acknowledgement of the emotional support of friends and family. I would like to thank my mother, father, Ivar, Eline and the rest of the extended family in Asker, for bringing home a little closer to Trondheim and for letting my take my mind off work whenever I've come to visit. Thanks to Per-Olof, Live, Tristan, Magne, and Rigmor for wonderful company and support in Trondheim. Cheers to all my friends in Troll-Ing. too, for great company, reminiscing about our study days, and occasionally hearing about what life is like after university. I also owe a lot of emotional stability to the company of everyone involved in H.M. Aarhønen. Thank you so much for still allowing me to hang out at the student office.

I would also like to mention the friends I have not met face to face, but whose online company has helped preserve my sanity by taking my mind off work and onto my various nerdy hobbies (as well as helping me learn better English) throughout these four years. Here's to DHR-107, Worldie, MikeAU, Altissimo, Smuckem, Blitzamirin, Mova, Gira, Hixee, Ian, Snoo, Hyde, Kimahri, Marnit, and all the others, I hope to meet you all someday.

Last, but not least, I would like to thank the gang at the office. Silje, Erin, Anna, Yingpeng, Hrefna, Bridget, Jørn Emil, Ingrid, and all the rest of you have made each day at work tremendously enjoyable, and often helped sorting out issues small and large as well. Also, a great thanks to the master's students throughout the years for helping me collect and make sense of data: Anna, Inger, Ida, Kristina, Martin, and Vegard, this work would have been a lot poorer without you.

Summary

Blue-green roofs are defined as a type of roof assembly wherein vegetation and various sub-layers are employed as part of a stormwater management strategy. This thesis discusses the risks of building defects associated with blue-green roofs. The work intersects three main fields of study: building/material science, stormwater management, and project/risk management.

While individual aspects of green roofs have been widely researched in literature, in fields such as hydrology, thermodynamics, urban landscaping, or building energy use, technical issues regarding their integration in the building envelope have received little attention. The aim of this thesis is to investigate potential risks associated with the large-scale adoption of blue-green roofs for stormwater management purposes in Norway.

Blue-green roofs exist in the concurrence between many different disciplines. During the thesis work, it quickly became evident that the research into the technical risks would necessarily need to span a broad range of disciplines as well. While the thesis is mainly restricted to engineering fields such as building science, material science, stormwater management, and project management, it was also found necessary to dabble a little bit into cognitive science to address the phenomenon of information overload. Obtaining a qualitative understanding of the main challenges was prioritized over in-depth research in either field.

The thesis work has identified a general lack of a systemic approach to blue-green roofs in scientific literature as well as in current approaches to quality risk management in the Norwegian building sector. The variety of disciplines involved presents a challenge in understanding and planning for the potential technical issues and conflicting interests in blue-green roof projects. A lack of in-depth research on the subject was also noted. The reasons for this may be related, as experts from several disciplines will necessarily have to be involved.

Fortunately, results also indicate that the technical challenges of blue-green roofs are already well understood within the separate disciplines. The requirements for a good stormwater management system are known in hydrology and the requirements for a good roof are known to building physics. The properties, requirements, and drawbacks of the various materials are familiar, and scheduling the assembly of the roof is fully feasible within the known limits of project management. However, this information is not necessarily widely known information *outside* of these respective fields, which makes it challenging for disciplines to achieve a common understanding of technical challenges and requirements. Thus, there exists a challenge in collating and presenting all the known information from multiple disciplines in such a way it becomes useful in a practical setting.

To this end, a suggested framework is presented, in the form of a checklist listing the primary quality risk concerns according to their main discipline and in their relevant project phases. It is intended to be consulted by project managers as a supplement to more exhaustive bodies of information such as the SINTEF Building Research Design Guides.

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2. Andenæs, E, Kvande, T, Muthanna, T.M & Lohne, J: Performance of Blue-Green Roofs in Cold Climates: A Scoping Review. *Buildings* 2018, Vol. 8(4), 55; doi:10.3390/buildings8040055, ISSN 2075-5309

Part 2: Current approach and challenges

3. Andenæs, E, Engebø, A, Time, B, Lohne, J, Torp, O & Kvande, T: Perspectives on Quality Risk in the Building Process of Blue-Green Roofs in Norway. *Buildings* 2020, Vol. 10(10), 189; doi:10.3390/buildings10100189, ISSN 2075-5309
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Complementary work carried out as part of the PhD study

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Stagrum, A.E, Kvande, T, Engebø, A, Andenæs, E & Lohne, J: Climate implication and adaptation measures for energy use in buildings – a scoping review. *Sustainable Built Environment SBE19* Helsinki, Finland, 22-24.05.2019

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Andenæs, E, Stagrum, A, Kvande, T & Lohne, J: Effects of Atmospheric Pressure on Water Absorption in Plastic Insulation – A Laboratory Investigation. *Journal of Testing and Evaluation* 2021, Vol 49; doi:10.1520/JTE20200337, ISSN 0090-3973

1. Introduction

1.1 Climate and climate change

The Norwegian climate poses many challenges to the built environment. Wind and precipitation, often in combination, impose a high moisture load on buildings and infrastructure, as well as on the terrain on which they are built. During spring and autumn, temperatures often oscillate around the freezing point as the sun sets and rises, creating cycles of freezing and thawing. The winters may bring heavy snow loads or bone-chilling cold spells that cause water to freeze and burst through its pipes. However, the Norwegians seem to consider it all worth it when summer finally arrives, with its warm, ever-lasting afternoons, temperate, quiet evenings, and short nights without darkness.

In more formal terms, the Norwegian climate is characterized as multi-climatic and dominated by maritime temperate and continental climate (Thodesen et al., 2018), categories C and D according to the Köppen-Geiger classification system (Peel et al., 2007). Polar climate (category E) is found in large parts of the country as well, although mainly in mountainous or remote areas with few urban settlements. A map of the climate zones of Norway and the Nordic countries is provided in Figure 1. The coasts experience a generally mild and wet climate, while inland regions receive warmer summers and colder winters (O'Brien et al., 2004). However, such generalizations may not necessarily be applicable on a smaller scale. The climate may vary greatly even within short distances in cities, as most cities in Norway are located along the coast where steep hills may provide significant elevation (and thus, temperature) differences within relatively small areas. Precipitation that falls as rain at sea level may fall as snow only a kilometre away, creating a different microclimate over the course of a season.

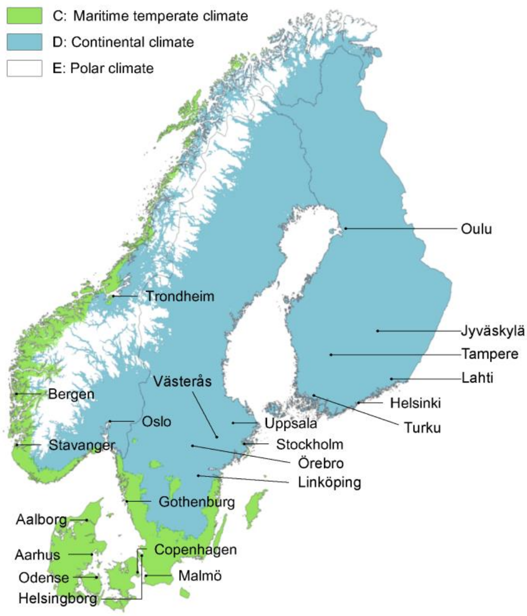

Figure 1: Map of the climate zones of the Nordic regions according to the Köppen-Geiger climate classification. Figure from Thodesen et al. (2018).

The harsh climate of Norway necessitates that buildings provide shelter during all seasons and in all weather. With outdoor conditions often being wet, cold, dark, and generally miserable, the refuge of a warm and dry building becomes even more precious. This requires robust buildings that maintain their functionality in their face of variable climate exposure throughout their entire lifetime, without needing excessive maintenance, repairs, or replacements (Lisø, 2006).

However, the climate is changing, following decades of carbon emissions from industrial activities into the atmosphere (Pachauri et al., 2015). In Norway, climate change brings a generally warmer climate, causing increased amounts of precipitation (Hanssen-Bauer et al., 2015). Climate change is expected to affect the built environment in several ways, imposing new threats to the functionality of the buildings we rely on for shelter (Flæte et al., 2010; KLD, 2013).

One specific concern relevant to this thesis is the issue of torrential precipitation events (Beguería and Vicente-Serrano, 2006; Lenderink et al., 2019; Steensen et al., 2011). These may appear as "rain cells" where a large amount of rainfall occurs within a limited area over a short duration. This phenomenon is challenging to forecast (Benestad and Haugen, 2007), and its impact on the built environment varies greatly depending on the precise location of its occurrence. A rain cell falling a kilometre offshore of a city may not even be noticed by its residents or register in statistics, and a kilometre inland it may fall harmlessly over uninhabited forest, but if it hits the city in the middle, significant flooding and damage may result. Ongoing work in the field of meteorology aims to improve the ability to forecast the occurrence and location of torrential rain events (Belušić et al., 2020; Lind et al., 2020).

1.2 Urbanisation and urban floods

The risks associated with increased rainfall are notable in urban areas, particularly in the face of urbanization of cities (Chen et al., 2015; Semadeni-Davies et al., 2008). Dense cityscapes provide few surfaces for stormwater to infiltrate into the ground, causing large amounts of surface runoff (Broekhuizen et al., 2019).

The traditional approach to surface runoff is to direct it into stormwater drains and pipes that take the water to a suitable downstream recipient (Burian and Edwards, 2012). However, with climate change, future torrential rainfall events are likely to exceed the design parameters of the existing stormwater pipe network, filling pipes and drains to capacity and leaving water to flood on the surface. Replacing the pipes would be a prohibitively expensive endeavour, and unlikely to find budget support considering the maintenance backlog of water and wastewater pipes in Norway (RIF, 2015). The combination of increased precipitation, urbanization, and a stormwater drainage network insufficient to manage the necessary volumes may pose severe challenges to urban areas (Chen et al., 2015). Dangers associated with urban flooding include water damage to basements, below-ground car parks and even metro systems, erosion of the soil layer which may damage infrastructure or building foundations, and pollution due to sewage overflow events (Nilsen et al., 2011). The high costs associated with urban flooding has spurred increased attention to stormwater management in recent decades. Legislation for the built environment is addressing the issue by mandating a certain level of attention towards stormwater management and climate adaptation.

1.3 Climate adaptation and stormwater management

Climate adapted buildings are defined by Grynning et al. (2020) as "Structures that are planned, designed, and built to withstand various types of external climactic stresses". This ideally includes both the climate in which the building is built and the climate the building is expected to meet in the future. From the perspective of the built environment in Norway, the increase of torrential rain is considered the most challenging aspect of climate change. The challenge is particularly evident in urban areas receiving an increased amount of stormwater (Time, 2020).

The Norwegian approach to managing stormwater and urban floods is called the "three-part strategy" (Lindholm et al., 2008). The three steps are illustrated in Figure 2.

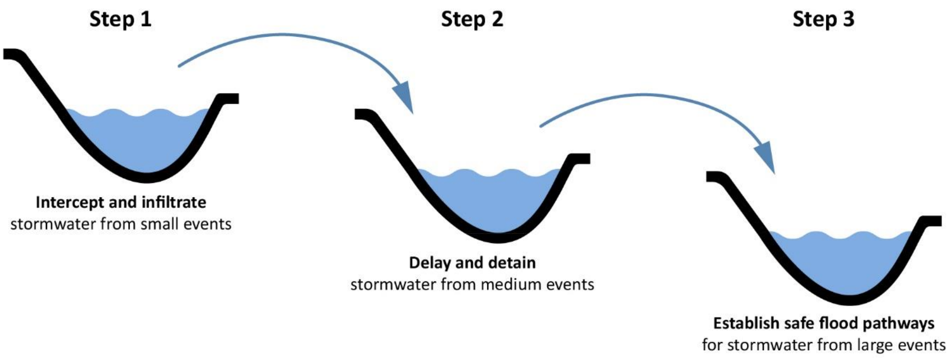

Figure 2: Norwegian three-step strategy for stormwater management. Illustration: Klima 2050/SINTEF.

A contemporary approach to the three-part strategy includes so-called "blue-green infrastructure". This term is used e.g. by Copenhagen Municipality in its stormwater management plan (Copenhagen Municipality, 2012). This family of stormwater management solutions achieves infiltration and runoff delay through a combination of "natural" solutions, such as beds of living plants or stormwater ponds. The term SUDS, Sustainable Urban Drainage Systems, is also used to describe blue-green infrastructure (Muthanna et al., 2018). The term "Nature-based solutions " (Lafortezza et al., 2018) is similar, but does not necessarily require the involvement of plants. The terminology of urban drainage is complex, and thoroughly discussed by Fletcher et al. (2015).

Blue-green infrastructure may also extend to building rooftops. In densely developed urban areas, rooftops may account for 40-50% of impervious surfaces (Stovin et al., 2012). Blue-green roofs are roofs where a combination of live vegetation, their growth medium, and eventual separate water storage layers are used to retain or detain runoff, greatly reducing roof runoff during extreme precipitation events (Hamouz et al., 2020; Shafique, Kim, et al., 2016). The overall runoff from green and blue-green roofs over time has also been shown to be lower than that of conventional roofs, due to evaporation and transpiration (evapotranspiration) (Bengtsson et al., 2005; Hamouz et al., 2018; Johannessen, 2020; Stovin et al., 2012). The hydrological performance of green roofs is also studied through simulations, e.g. by Pettersson (2021). Extensive use of rooftop areas to retain stormwater may therefore play a vital role in achieving the goal of the second step of the three-part strategy. Retaining roof runoff will reduce stormwater on the surface by an amount proportional to the relative area of rooftops in the cityscape, leaving volumes of surface stormwater that can be managed by existing stormwater infrastructure. Figure 3 illustrates examples of how the three-step strategy can be applied in practice. Blue-green roofs serve the most notable role in step 2, serving as a detention volume to delay stormwater runoff.

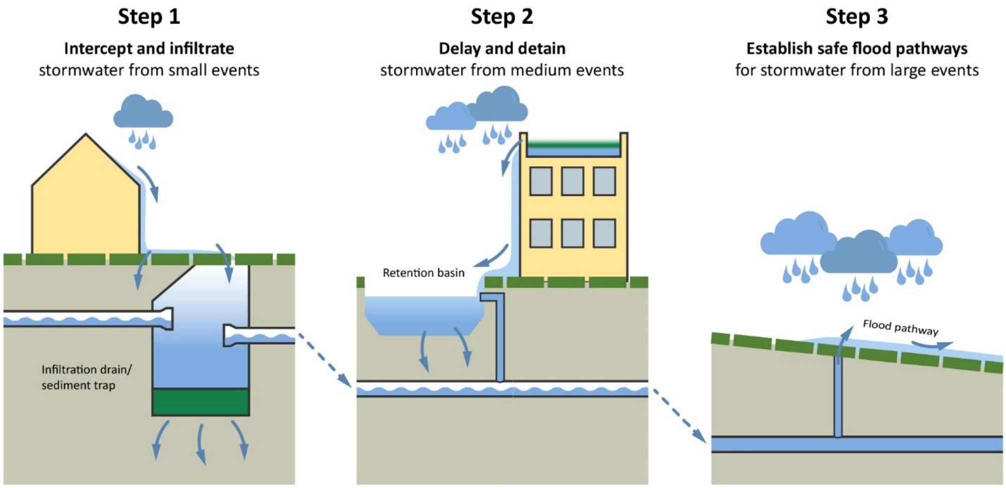

Figure 3: Examples of practical applications of the three-step method for stormwater management. Illustration: Klima 2050/SINTEF.

However, while serving its functionality as a stormwater management solution, a blue-green roof still needs to be a roof first and foremost. It needs to serve as an effective barrier between the outdoor climate exposure and a stable indoor climate of a building. A building envelope must be robust in the face of climatic loads, without needing excessive maintenance or frequent repairs. This functionality of protection must not be compromised as the roof is given additional purposes: Water damage in the attic due to roof leaks is just as undesirable as water damage in the basement due to flooding.

1.4 Norwegian legislation

Ensuring the key functions of a building, including climate robustness, is the purpose of the Norwegian building regulations. The principal structure of Norwegian building legislation is described by Lisø et al. (2017), Skatland et al. (2018), and Stenstad (2014) and illustrated in Figure 4. The overall objectives of the building code are specified in the Planning and Building Act (KMD, 2008), and quantified in the Technical Regulations. As of the writing of this thesis, the technical regulations were last updated in 2017, giving the current version the name TEK17 (DiBK, 2017). The Guideline Addendum to Technical regulations (VTEK) present pre-accepted solutions to the requirements of TEK17. The regulatory measures are completed by VTEK and other guidelines, circulars, and official reports. The individual building projects must also verify that the regulations are followed through individual analysis. Tools to this end include pre-accepted solutions such as those presented in the SINTEF Building Research Design Guides (no: Byggforskserien), standardization documents, and certification of products. Individual analysis is always required unless pre-accepted solutions are followed.

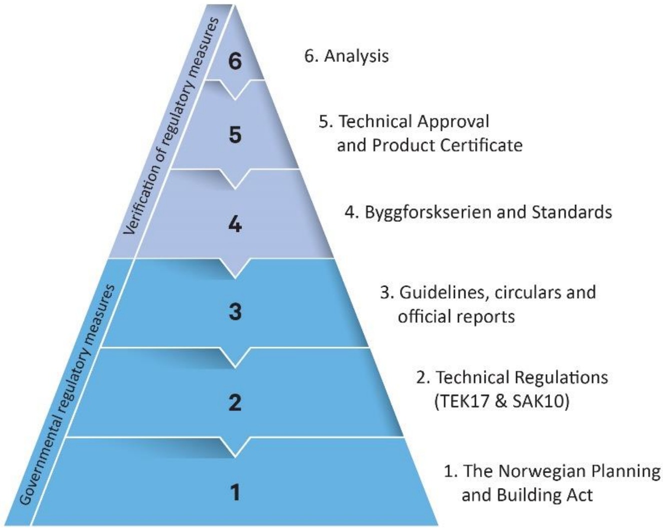

Figure 4: The hierarchical structure of the Norwegian building legislation. Figure adapted from (Lisø et al., 2017).

The requirements in the Technical Regulations is based on function, instead of mandating the use of specific solutions or materials. Any solution may be accepted, provided the functional requirements are met. This means that TEK17's approach to climate adaptation is relatively robust through its simplicity. As stated in §7-1: "*(1) Buildings must be located, designed, and built so that it achieves a satisfactory safety against damage or significant disadvantages from exposure to nature. (2) Measures must be designed and built so that buildings, building sites, and adjacent terrain is not exposed to damage or significant disadvantage resulting from the measure"* (author's translation).

Climate adaptation presents a practical challenge to the concretization of legislative requirements. A building is required to be designed to withstand climatic loads throughout its lifetime. Design climatic loads are available in Norwegian standards, but these are based on historical data. Because of climate change, climatic loads are expected to change over the lifetime of a building, but tools to quantify future climatic loads are not available. Given the uncertainty inherent in future climate predictions, especially on a local scale, the design loads that can be obtained are approximative at best (Benestad et al., 2016; Hanssen-Bauer et al., 2015). Documenting that climate adaptation requirements are met is as such not currently possible in practice.

As illustrated in Figure 4, the Planning and Building Act and the Technical Regulations form the legislative base for building projects in Norway. Beyond this level, requirements may be detailed on a municipal level or specified in standards. Note that as legislation becomes more detailed, it also becomes more fragmented, with a greater multitude of documents giving specifications to a variety of disciplines with different areas of responsibility. The structure of the legislation is shown as a pyramid in Figure 4, but its practical nature is fractal.

The various components of the legislation often interact with several disciplines. The interaction of different disciplines presents many diverse challenges, notable among which is the delegation of ownership to a design or building element. The example of roof runoff is discussed in section 5.2, illustrating how different disciplines may have very different perspectives on the requirements of the same building element. Likewise, individual pieces of legislation may require measures or solutions that are inconvenient or complicated seen from the perspective of another discipline.

1.5 Blue-green roofs

Blue-green roofs are an example of a building element facing the challenges of needing to fulfil multiple requirements and performing multiple functions within several different disciplines. As implied by the name, blue-green roofs can be considered a fusion of blue-green infrastructure and green roofs. In general terms, they are roofs built for the purpose of stormwater management, which is achieved using a roof assembly including live plants. However, there is yet to be developed an exact and widely adopted definition of what constitutes a blue-green roof – or more specifically, what separates a blue-green roof from an ordinary green roof.

An initial definition of blue-green roofs used in **Paper 2** in this thesis suggests that "any green roof becomes a blue-green roof if it is built explicitly as part of a stormwater management system." This initial definition was compiled by the authors but not sufficiently grounded in international literature. A more formal definition by Shafique et al. (2016) suggests that blue-green roofs provide both detention and retention of water, while ordinary green roofs only provide detention. Martin and Kaye (2020) put it simpler: "A green–blue roof is a blue roof located beneath a green roof system". Note that it has not yet been settled whether "blue-green roof" or "green-blue roof" is the appropriate spelling of the term.

It may also be argued that the term "blue-green roof" is fundamentally inadequate as a technical descriptive term. It does not sufficiently describe the function, purpose, or assembly of the roof. The terms "detention-based green roof" appears to be more favoured by hydrologists (Hamouz et al., 2020). In fact, it may appear that the term "blue-green roof" sees little use outside of Klima 2050, and that future publications will transition to use of more widely accepted terminology. However, for this thesis, the term "blue-green roof" is used throughout.

For blue-green roofs to be an effective solution for stormwater management, they need to be adopted on a large scale in the urban cityscape. For wide adoption to be successful, the roofs need to maintain the quality of the building on a level comparable to conventional roof solutions. A primary motivation for this thesis has been to develop methods to ensure the building technical quality of blue-green roofs in a Norwegian climate.

The main elements of a blue-green roof are illustrated in Figure 5. The blue-green roof assembly needs to coexist alongside elements of a conventional roof such as parapets, drains, mounting systems for technical equipment, and adjoining walls. A level of traffic may also occur on the roof, for maintenance or leisure. Overall, the roof is a complex part of a building with many details to consider. Many different technical disciplines are also involved, imposing a variety of requirements on the roof. Figure 6 shows what a blue-green roof may look like in practice (although this particular roof has not been designed for stormwater management). Section 3.1 discusses the composition of blue-green roofs in greater detail.

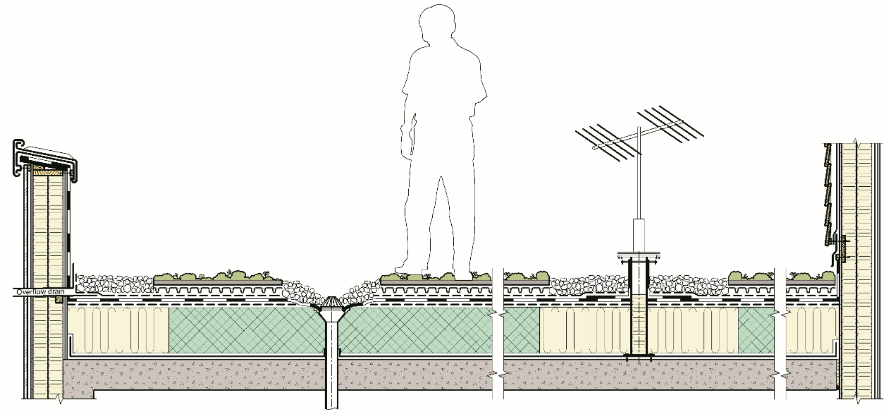

Figure 5: Main design components of a blue-green roof based on a conventional compact roof. From left to right: Parapets, drains, areas of traffic, equipment mounting brackets, and adjoining walls. Note the use of non-flammable insulation and gravel cover where mandated. Illustration: Klima 2050/SINTEF.

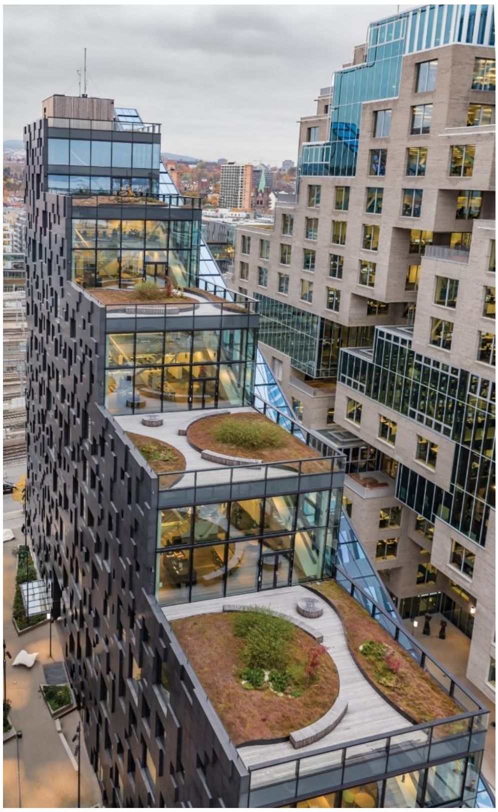

Figure 6: Green roof mounted on an office building in central Oslo, illustrating the practical use of blue-green roofs. Photo: Bergknapp AS.

1.6 Defects and quality risk

A particular challenge associated with green and blue-green roofs is that the green roof assembly covers the roof membrane, which is the primary waterproofing layer in a compact roof. Defects in the roofing layer will be difficult to discover and expensive to repair after the roof has been fully assembled, due to the need to remove the blue-green layers to conduct repairs. Additionally, intruded water may accumulate over many years in a compact roof before the leak is eventually discovered, at which point substantial repairs are required to restore the roof to its original standard. It is therefore imperative to avoid defects in the waterproofing layer, as the consequences of defects may be much greater than is the case for conventional compact roofs. Skjeldrum and Kvande (2017) revealed a need for a system to manage building defects for blue-green roofs. This thesis is largely inspired by that work.

In this thesis, the word "building defect" is used to describe building damages or flaws that compromise the quality of a building or building part. It can be considered the potential outcome, or actuality, of quality risk. Ingvaldsen (2001) remarks that the terminology of building defects is not defined with sufficient rigidity. The definition of "building defect" used by Ingvaldsen is "Negative deviation [from specified requirements] that is not accepted by the owner of a building or building project". This definition does not encompass damages to the building by Ingvaldsen's definition (as this is treated as a separate category), but it will for the purposes of this thesis. Ingvaldsen also introduces the term *"Prosessforårsakede byggskader"* (Norwegian), which may be translated as "Process-induced building defects". These are building defects caused during the planning, design, or construction stages of a building project, including the manufacturing of building materials.

This term is further explored by Kvande and Lisø (2010), who define "Process-induced building defects" as all defects caused by flaws in the as-built building, in addition to defects caused by faulty repair work. The three main categories of causes of building defects as defined by Kvande and Lisø are flawed construction, flawed maintenance, and erroneous use.

Comprehensive, quantitative data on building defects has not been systematically collected in Norway. While some quantitative research has been carried out on building defects (Bunkholt et al., 2021; Buys and Roux, 2013; Forcada et al., 2013; Gullbrekken et al., 2016; Lisø et al., 2006), the data sets are limited to defect cases gathered by one single entity, typically an advisory agency (such as SINTEF), an insurance company, or from court cases. The data sets only contain building defects where the entity in question has been involved, creating a sample bias in any research conducted on the dataset. The Norwegian Building Authority (no: Direktoratet for byggkvalitet, DiBK) has a mandate to create a comprehensive national database of building defects, but this has yet to materialize. The most recent mention of this database in literature stems from 2009 (Lisø and Rolstad, 2009). A government whitepaper from 2012 notes a general lack of information about the state of the building stock in Norway (KMD, 2012). Similar challenges with the limited availability of comprehensive defect data have been noted in international sources, such as Josephson and Hammarlund (1999) and Lopez and Love (2012).

Quality risk is defined in this thesis as the risk of building defects. That is, the consequences of building defects and their probability of occurring. The relationship between the terms "building defect" and "quality risk" is that the latter is the potentiality of the former. Risk is discussed in further detail in section 3.2.

1.7 Definitions

In this thesis, the following definitions are used:

- **Blue roof:** A roof modified to allow temporary water storage, to function as part of a stormwater management strategy. A term derived from "blue infrastructure".
- **Blue-green roof:** A roof assembly wherein vegetation and various sub-layers are used as part of a stormwater management strategy. A sub-category of blue roofs and of green roofs.
- **Blue-grey roof:** A roof assembly functionally identical to a blue-green roof, but with pavers or other cover instead of vegetation. Suitable for roof traffic.
- **Building defect:** Building damage or flaw that compromises the quality of the building or building part. The actuality of quality risk (Ingvaldsen, 2001).
- **Compact roof:** Roof assembly without ventilation cavities, creating a continuous "sandwich" structure of material layers from the interior to the exterior side. Also known as "un-ventilated roof" or "warm roof" (Noreng, 2018).
- **Conventional (compact) roof:** (Compact) roof assembly where the roofing forms the exterior layer and the roof serves no purpose beyond being a building envelope (Noreng, 2018). Sometimes called a "black roof" in hydrology literature.
- **Design guide:** Guideline documents for building design published by SINTEF Community (no: Byggforskserien). Occasionally referred to by their full name, SINTEF Building Research Design Guides (SINTEF, n.d.).
- **Detention:** The quantified delay of the runoff of stormwater, both in time and capacity (Johannessen, 2020).
- **Evapotranspiration:** Evaporation and transpiration of water on a blue-green roof (Johannessen, 2020).
- **Extensive green roof:** Thin, light-weight green roof assembly built to harbour small plants. Substrate thickness <100 mm (FLL, 2008).
- **Green roof:** Roof assembly wherein plants (intentionally) grow on the outer roof surface. May be extensive, semi-intensive, or intensive (FLL, 2008).
- **Intensive green roof:** Green roof assembly built to harbour large plants (shrubbery-sized or bigger), usually to form a rooftop park. Substrate thickness > 150 mm (FLL, 2008).
- **Inverted roof:** (Compact) roof assembly where some or all the insulation is located above the waterproofing layer (Noreng, 2018).
- **Project delivery model:** A system for organizing and financing design, construction, operations and maintenance activities that facilitates the delivery of a good or service (verbatim definition by Miller et al. (2000)).
- **Quality:** Meeting the legal, aesthetic, and functional requirements of a project (verbatim definition by Arditi and Gunaydin (1997))
- **Quality risk:** The consequences of building defects, and their likelihood of occurring. The potentiality of building defects.
- **Retention:** The quantified reduction of the runoff of stormwater, i.e. the amount of water evaporated and transpired from a blue-green roof (Stovin, 2010).
- **Risk:** A synthesis of the probability and consequences of <u>unwanted</u> events (Johansen, 2015). See also Uncertainty.

- **Roofing:** The outer waterproofing layer of a compact roof (Noreng, 2018). For ventilated roofs, the roofing is the exterior weatherproofing layer such as tiles, shingles, or metal sheets.
- **Roof membrane:** Sometimes used synonymously with roofing, as a roof membrane forms the waterproofing layer of a compact roof. However, the term “membrane” is more appropriate where the waterproofing layer is not the exterior layer of the roof, such as in inverted roofs (Noreng, 2008).
- **Semi-intensive green roof:** Green roof assembly of a thickness between that of extensive and intensive roofs. Built for roof lawns and some landscaping, but usually not large plants. Substrate thickness 100-200 mm (FLL, 2008).
- **Stormwater:** Precipitation water flowing on the ground or roof surface.
- **Turf roof/Sod roof:** Traditional Scandinavian green roof assembly, often involving turf of thickness of 100-300 mm (Larsen, 2009). Excluded from the scope of this thesis as they usually include an air cavity between the roof waterproofing and the underlayer roof.
- **Uncertainty:** A synthesis of the probability and consequences of events that may affect the project’s outcome (Johansen, 2015). May be positive (opportunities) or negative (risks).

2. Thesis outline

2.1 Objective & Scope

The principal objective of the research has been grounded in the following idea: Given a likely large-scale adoption of blue-green roofs in Norway, what are the potential building technical hazards and risks, and how can we avoid them? Modern green roofs are still uncommon and relatively novel in Norway, and their long-term technical performance under Norwegian conditions remains unclear. History shows that adoption of new technology by the building sector has not always gone smoothly. In the past, adoption of novel building materials and elements on a large scale have caused building defects due to a lack of knowledge about their drawbacks or about their requirements for successful use. Examples include the historical use of unhealthy materials like asbestos and PCBs (Andersson et al., 2004), and air quality problems in early single-family dwellings designed for mechanical ventilation, because the occupants tended to turn the ventilation off (Granum and Haugen, 1986). In Denmark, Magnesium oxide boards became a popular material for façade cladding over a five-year period before its poor suitability for the climate was discovered. The damages incurred a cost of around 2 billion DKK, 200 million € (Rode et al., 2017).

The examples illustrate a need to assess risks before adopting a novel building material or technology on a large scale. This is also true of blue-green roofs. A prospective risk assessment of the concept and a framework to manage this risk is essential to avoid expensive future problems.

2.2 Research questions

Three research questions have been formulated to shape the research. They include an assessment of quality risk management as currently understood in the Norwegian building sector and in research literature, identifying where the current methods are inadequate, and a proposal for future improvement through a risk management framework.

1. *Motivation, state of the art* – What is known in literature about quality risk pertaining to climate adaptation of buildings in general and green roofs in particular?
2. *Current approach and challenges* – What is the current system-level approach towards management of quality risk for green roofs in Norway?
3. *Suggestions* – How can quality risk management for green roofs be improved?

2.3 Limitations

Certain limitations apply to the research. Experts in either of the three major fields touched upon by the thesis (building materials, hydrology, and project/risk management) may notice that the research has not conducted an in-depth dive into their issues and challenges. There is no novel modelling of runoff response to precipitation events, no statistical analysis on the aging of bituminous roof membranes, and no advanced managerial theory of risk tree models. Given the natural limitations of time and resources (and, as may be noted to have a certain relevance, mental capacity), spanning broadly has been prioritized over in-depth studies of singular topics. A qualitative approach has been selected to obtain an understanding of quality risk issues covering as many of the relevant fields as possible.

The research has been conducted in a Norwegian context, with the Norwegian legislative situation as a background. Research in Part 1 of the thesis has identified that the primary concerns in a Norwegian context does not always align with focus areas of international research. For instance, the use of green roofs as an energy savings measure dominates research literature but is almost completely absent in Norway. Likewise, in Norway, drought is not a major concern. Conversely, little international research has been found involving the challenges buildings face under increased levels of precipitation (Stagrum et al., 2020).

Nevertheless, even within these limitations it has not been possible to span every conceivable field and discipline touched upon by blue-green roofs. Disciplines that have been identified to have importance to the design of green roofs, but which have not been studied in detail, include fire engineering, pollution analysis (particularly in the form of roof water runoff), plant horticulture, biodiversity, ecology, landscape architecture, and economics.

The background of the author may also influence which quality risk issues are considered the most pressing or important. The main investigated discipline in this thesis has been that of building materials and related fields, with water intrusion into the building envelope seen as the greatest threat to be avoided. This prioritization may not be universal. A horticulturalist would presumably place greater importance on the survival and development of plants instead, while a hydrologist might list any threats to the hydrological capabilities of the roof as the greatest cause for concern.

Conversely, there exists a bias in the perception of the *least* important issues, which may lead to certain quality risk factors being overlooked or under-communicated. The thesis work has shown that awareness of quality risk factors outside of the individual's primary discipline is an important issue to be addressed in green roof projects. Equally, the issue exists on a meta level of risk assessment research as well.

Likewise, bias – or lack of awareness, in some cases – may cause some unintended misuse of terminology. Proper use of terms is a challenge even within a single research discipline. This challenge is exacerbated when collating results from multiple disciplines. As an example, the term "blue-green roof" itself can be considered serviceable for the purposes of one discipline, while unacceptably imprecise from the perspectives of another. To a building physicist, the term may adequately communicate the relevant considerations that will have to be made: constantly high levels of moisture, presence of plant roots, lack of direct sunlight at the roof membrane, etc. Meanwhile, to experts of horticulture or stormwater management, the term "blue-green roof" on its own fails to describe the type of roof vegetation or the roof's hydrological purpose (retention/detention, capacity, etc.). The nomenclature of blue-green roofs is further discussed in Section 1.5 of this thesis. Comparable disputes of terminology are found whenever disciplines interact, and this thesis includes many interacting disciplines.

2.4 Structure of the work

The thesis is divided into three main parts, reflecting the three research questions:

2.4.1 Motivation, state of the art (papers 1 and 2)

The initial phase of the research focused on charting the state of the art of research of climate adaptation and blue-green roofs, and is presented in **Papers 1** and **2.** The research was conducted through scoping literature studies, as described by Arksey and O'Malley (2005). The scoping study method has also been used on a smaller scale for information gathering throughout the later studies as well.

The main author of **Paper 1** is Anna E. Stagrum, former PhD. candidate in Klima 2050. It provides an overview of research literature on climate adaptation of buildings, in which blue-green roofs may serve as a notable measure. Note that **Paper 1** is written after **Paper 2** was already published. Results from

Paper 2 motivated a study with a broader focus on climate adaptation. The research design is strongly inspired by **Paper 2**.

Paper 2 was written to provide an overview of research on green roofs from a building science perspective. The article presents a literature review of green roof research from all over the world, with a focus on implications for the operation of blue-green roofs in cold climates. Mapping the extent of recent research into blue-green roofs was central to this research phase, but even more importantly, scoping studies made it possible to find knowledge gaps in the literature that would guide the research going forward.

List of Papers

1. Stagrum, A.E, Andenæs, E, Kvande, T & Lohne, J: Climate Change Adaptation Measures for Buildings—A Scoping Review. *Sustainability* 2020, Vol 12(5), 1721; doi:10.3390/su12051721, ISSN 2071-1050
2. Andenæs, E, Kvande, T, Muthanna, T.M & Lohne, J: Performance of Blue-Green Roofs in Cold Climates: A Scoping Review. *Buildings* 2018, Vol. 8(4), p. 55; doi:10.3390/buildings8040055, ISSN 2075-5309

2.4.2 Current approach and challenges (papers 3 and 4)

The second part of the thesis focuses on quality risk and quality risk management. Through collaboration with experts of project management, it was investigated how knowledge of blue-green roofs was used in industry settings throughout the Norwegian building sector.

For **Paper 3**, Interviews and document studies were conducted to create a picture of quality risk understanding from the perspective of different actors within the Norwegian building sector. The paper collects and collates findings from several phases of research published individually in a series of conference papers (Andenæs, Engebø, et al., 2019; Andenæs, Time, et al., 2019a, 2019b), as well as preliminary results from **Paper 4**.

Paper 4 focuses on a widely used tool that is considered a key measure used to reduce quality risk in the Norwegian building sector: The SINTEF Building Research Design Guides. Data collection from the Building Design Guides was initially performed to gather recommendations relevant to the design of blue-green roofs, but it was discovered that the extent of information presented in the guidelines in itself may create a quality risk challenge. The paper gives an overview of the SINTEF Building Research Design Guides, a lesson from cognitive science, and how there is significant room for improvement in the overall structure of information in the design guides.

List of Papers

3. Andenæs, E, Engebø, A, Time, B, Lohne, J, Torp, O & Kvande, T: Perspectives on Quality Risk in the Building Process of Blue-Green Roofs in Norway. *Buildings* 2020, Vol 10(10), 189; doi:10.3390/buildings10100189, ISSN 2075-5309
4. Andenæs, E, Time, B, Kvande, T & Lohne, J: Surpassing the Limits to Human Cognition? On the Level of Detail in the Norwegian Building Design Guides. *Journal of Civil Engineering and Architecture* 2021, Vol 15, p. 103-117; doi:10.17265/1934-7359/2021.02.006, ISSN 1934-7359

2.4.3 Suggestions for quality risk assessment (paper 5)

The final part of the thesis, **Paper 5,** suggests improvements for the management of quality risk for blue-green roofs, based on the deficiencies observed in the second part. It was understood at this point that the obstacles to successful risk management of blue-green roofs was not primarily technical in nature, but processual. Inspired by other risk management frameworks, a proposed framework for quality risk management is presented.

List of Paper

5. Andenæs, E, Time, B, Muthanna, T.M, Asphaug, S & Kvande, T: Risk Reduction Framework for Blue-Green Roofs. *Buildings* 2021, Vol 11(5), 185; doi:10.3390/buildings11050185, ISSN 2075-5309

3. Theoretical framework

3.1 Blue-green roofs

3.1.1 Purpose and objectives

Green, blue-green, and blue-grey roofs may be applied in several different contexts in urban building projects. Figure 7 illustrates some potential applications of such roofs in a typical building project. Intensive green roofs can be used to form a podium level between tower blocks, covering a parking garage or commercial space belowground or on ground level. Semi-intensive green roofs and blue-grey roofs form rooftop gardens and recreational space. Extensive green roofs typically cover rooftop areas inaccessible to the public.

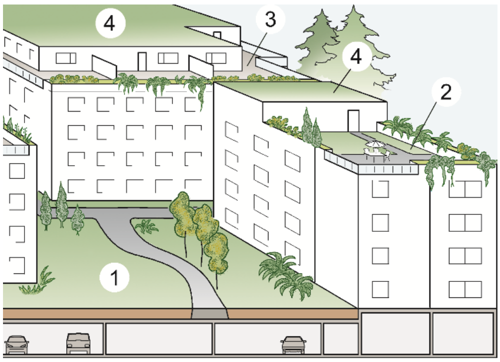

Figure 7: Applications of green roofs in a typical construction project: 1) Intensive green roof, forming a lawn or park area, 2) Semi-intensive green roof, creating a «rooftop garden», 3) Blue-grey roof, allowing both roof traffic and water detention, 4) Extensive green roof on building rooftops, not intended for public access. Illustration: Klima 2050/SINTEF.

While it is inherent to the concept of blue-green roof that they primarily serve a stormwater management function, green roofs may be built for several other reasons. In warmer climates, the evaporative cooling effect of green roofs, as well as their insulation capabilities, contribute to reducing cooling costs for buildings, making green roofs an effective cost savings measure (Ascione et al., 2013; Mahmoud et al., 2017; Niachou et al., 2001; Niu et al., 2010). However, while building cooling is required to some degree in Norway (Haase et al., 2013), this need is vastly less prominent than in other countries due to Norway having a colder climate and stricter insulation requirements. The insulating effect of a 100 mm thick green roof has been estimated to be below 1 % of the insulation requirements of a roof structure in Norway (Undheim, 2018). A Swedish study on a well-insulated building in a sub-Arctic climate found only a marginal energy benefit of a green roof (Schade et al., 2021).

Green roofs may also be built for aesthetical reasons, which could involve giving the building a "green image" or to provide green space for its occupants – ranging from the decorative function of an inaccessible sedum roof (Loder, 2014) to establishing a public park on top of subterranean facilities (Nektarios et al., 2014). The addition of green roofs to residential buildings has been found to increase their real estate value (Ichihara and Cohen, 2011), which presents an economic argument for their inclusion in a project even if other benefits are ignored.

Green roofs also have some positive impacts concerning biodiversity (Nagase and Dunnett, 2013), acoustics (Galbrun and Scerri, 2017), pollution (Rowe, 2011; Speak et al., 2012) and protection of the roof waterproofing layer (Björk, 2004; Köhler and Poll, 2010). Green roofs are considered compliant with EU minimum requirements for the fire resistance of roofing materials (bRoof t2) meaning they give some light fire protection to a roof (FLL, 2008). In this thesis, the building of green roofs for other specific purposes than stormwater management is not addressed in detail, and the associated technical challenges are considered equivalent for all purposes of green and blue-green roofs.

On a conceptual level, the reasons for the inclusion of blue-green roofs in a project can be sorted into two main categories: the roof is either constructed at the initiative of the project owner, or to satisfy an externally imposed requirement, such as laws or zoning regulations. The impetus for the roof's construction will likely influence the ambition and level of attention to detail in the roof project. However, it will always be important to pay attention to quality risks in blue-green roofs, even if they are only included in a project because they are mandated and there is no enthusiasm for it among participants.

Additionally, the design process of a blue-green roof will be affected by the roof's primary intended purpose. For instance, a housing developer may desire a rooftop garden as a selling point for apartments in the buildings, giving accessibility and aesthetics priority over blue-green functionality. A roof built solely for stormwater management may not consider aesthetics or biodiversity. Awareness of the primary purpose of the roof will help guide decisions to achieve its strategic goals.

3.1.2 Composition

The typical structure of a blue-green roof is illustrated in Figure 8. The exterior surface of the roof is covered with plants, rooted in a growth medium. Beneath the growth medium, another layer provides water storage and drainage. Several different solutions exist for this layer of water storage. For extensive blue-green roofs, cups in a perforated dimple membrane, as illustrated in Figure 9, may be preferred. Water storage may also be achieved through water storage boxes (Shafique, Lee, et al., 2016), pores in a porous medium such as Leca (Hamouz et al., 2018), mineral wool (Vacek and Matějka, 2016), or water may even be pooled directly on the roof membrane (Protan, 2019). In all cases but the latter, the capacity for the roof to detain water is determined by the capacity of the storage material. If water is pooled directly on the membrane, it is common to detain water by restricting the flow through the roof's drains. Emergency overflow drains prevent water from pooling to a level beyond the structural capacity of the roof.

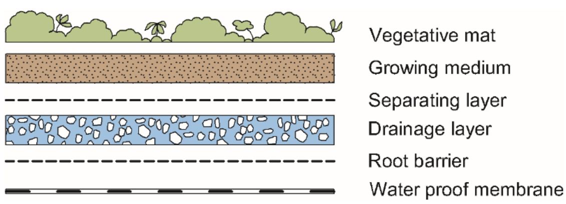

Figure 8: Principal structure of a blue-green roof. Figure from Thodesen et al. (2018).

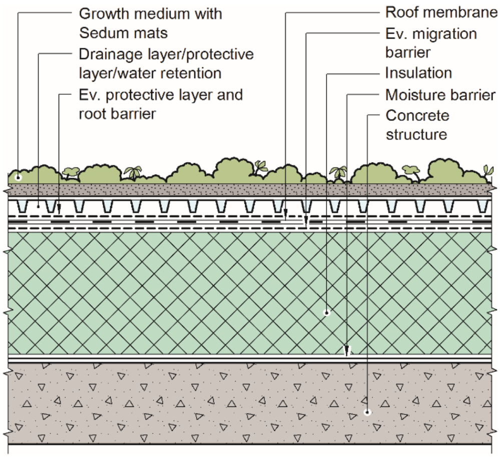

Figure 9: Typical blue-green roof assembly, in the form of an extensive Sedum roof. Illustration: Klima 2050/SINTEF.

An alternate variant of blue-green roofs is the so-called "blue-grey roof" (Hamouz and Muthanna, 2019), which is a type of blue roof assembly built to withstand traffic, achieved by using permeable concrete pavers over the drainage layer, rather than vegetation. This roof type has yet to see widespread adoption as of the writing of this thesis, and the term is not widely used. For the purposes of this thesis, blue-grey roofs are considered equivalent to blue-green roofs, as they share most quality risk concerns.

Common to most forms of blue-green roofs is that they are typically mounted on top of conventional compact roof assemblies. These are roofs without air cavities, typically laid at a flat or shallow (< 6°) angle (Noreng, 2018). Compact roofs typically lack any sort of drying capacity, relying on moisture-proof barriers on the internal and external sides to keep water out. A consequence is that if water intrudes anyway, it may accumulate and not easily dry out again. Water intrusion into a building construction may compromise its insulation properties, foster the growth of biological matter (i.e. fungi and bacteria), and deteriorate building materials. Water intrusion is possibly the foremost threat to the long-term integrity of a building envelope (Lisø, 2006).

The main assembly of a blue-green roof, as illustrated in Figure 8, merely forms the outer layers of the building's roof structure. The design, construction, and operation of a roof is a complex process even for conventional roofs, with a multitude of disciplines involved in defining the premises of the roof and its many individual detail components. Table 1 lists the disciplines, activities, and trades involved in the building of a roof throughout a building project, many of which will include activity on the roof during its operational lifespan. This complexity adds to the challenge of quality risk assessment, as actions by any actor has the potential to compromise the quality goals of any other.

Table 1: Disciplines involved in the building process of a blue-green roof during three main stages of the project.

Pre-construction (planning/pre-design/design)	**Construction**	**Post-construction (Operation/maintenance)**
• Architecture • Building physics/materials • Hydrology • Structural engineering • Landscaping / horticulture • Fire engineering • HVAC engineering • Electronics • Environmental- and lifecycle assessment • Legislative limitations/ requirements	• Carpentry • Roofing • Concrete pouring • Insulation • Plumbing • Gardening • Electronics • HVAC installation • Weatherproofing • Installation of rooftop technical equipment (telecom, signs, billboards, solar panels, etc.) • Installation of rooftop non-technical equipment (terrace flooring, railings, access doors, staircases, skylights, etc.) • Painting/coating	• Gardening • Recreational activities • MOM operations • Snow removal • Maintenance of HVAC equipment • Telecom operations • Billboards/signs • Solar panels • Weather monitoring

3.2 The building process

The process of a building project is typically divided into phases. While many phase models and project delivery models exist, this thesis primarily uses the “next step” model as described by Tiltnes (2015). Regardless of project delivery model, the actors and activities involved in a building project are generally the same, although they may be organized differently. A common delivery model in Norway is the design-build (DB) scheme, which is illustrated in Figure 10. In a DB scheme, the main contractor is responsible for organizing the design and construction process. This is opposed to the design-bid-build (DBB) scheme, where the main contractor is involved only after the design process is finished.

A common challenge of building projects is coordinating the process. A multitude of different actors are involved (as seen in Table 1), with different responsibilities, priorities, and measures of success. Perceptions of critical issues may also differ greatly between actors, necessitating coordination and cross-disciplinary cooperation.

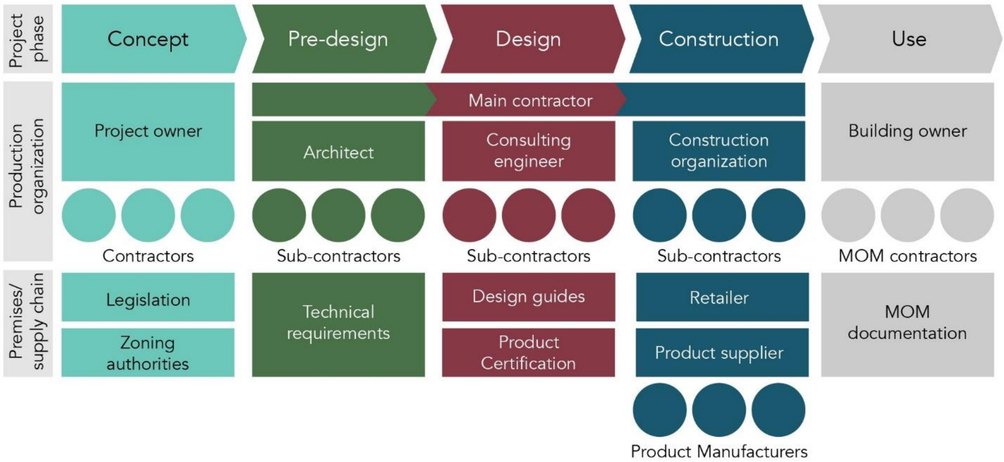

Figure 10: The project phases and main involved actors in a building project, here illustrated by a design-build scheme. Note that the main involved actors and activities will be present in the project regardless of the delivery model. Illustration: Klima 2050/SINTEF.

3.3 Risk and building defects

Despite – or possibly, because of – its very widespread use, the term "Risk" has no singular and universally agreed-upon definition. Johansen (2015) gathered several pages of proposed definitions of risk and uncertainty used throughout history, without reaching to a conclusive wording of a definition. ISO 31000 (2018) defines risk as "the effect of uncertainty on objectives". Similarly – but not identically – The Project Management Institute PMBOK (2013) defines risk as "the effects of uncertainty on project outcomes". Rausand (2013) defines risk as the answer to the three questions: "1) What can go wrong? 2) What is the likelihood of that happening?, and 3) What are the consequences?"

Common to all identified definitions of risk is a synthesis of the probability of unwanted events occurring, and the consequences of said events. Additionally, opinions are divided on whether "risk" is even an appropriate term at all. Instead, "uncertainty" is preferred by some, as it covers both positive and negative effects that affect the project's outcome (Johansen, 2015; Torp et al., 2018). In this context, risk is considered the "negative half" of uncertainty. This thesis will primarily use the term risk, as only the potential for negative effects is considered.

Risk assessment is, in the definition used by Rausand (2013), *the overall process of risk analysis and risk evaluation*. Risk analysis is *[a] systematic use of available information to identify hazards and estimate risk*, whereas risk evaluation concerns judgement of what risk can be tolerated.

Risk analysis may be quantitative or qualitative. Quantitative risk analysis assigns numerical estimates for probabilities and/or consequences, while qualitative analysis determine probabilities and consequences qualitatively (Rausand, 2013). Various models and tools can be employed for structured risk analysis, which may be qualitative or quantitative. Common models include the so-called "fault tree" and "consequence tree", used to analyse, respectively, the combination of basic events that lead to a critical event and the factors that determine the consequences of the critical event. The use of these models requires the relationships between factors and events (such as cause and effect) to be known, and for quantitative analysis the probability of each event occurring must also be estimated. A limitation of these models is that each analysis “tree” concerns one critical event, such as for instance the initiation of a leak or the failure of a system component. Fault- and event trees become inherently complex and may be unsuitable for analysing systems where multiple, sometimes unforeseen, failures can occur.

Other types of models are also commonly applied in systematic risk analysis. Notable among these are “Hazard and operability studies” (HAZOP) and “Failure mode, effects, and criticality analysis” (FMECA). These hazard identification processes analyse the systems component by component, creating a bottom-up risk analysis of complex systems. They were originally developed for the chemical industry and are best applied to analysing processing plants (Rausand, 2013). An overall focus on single-point failures and a lack of accounting for human error make these models poorly suited for analysing the risk of building defects in general, although they may be helpful when analysing the performance of one building component or the risk of one specific type of defect.

Other systematic risk analysis models are described by Rausand (2013). For this thesis work, it has been determined that systematic risk analysis would not be feasible for multiple reasons: a lack of data about building defects, the uncertain relationship between the general causes and effects of building defects, the amount of resources required to undertake a thorough analysis, and the inherent uniqueness of building projects that makes general analysis unfeasible. It has been decided not to employ these structured risk analysis models in this thesis, focusing instead on the overall nature and relationship of risk factors of blue-green roofs to benefit future systematic analyses.

Risk management literature conventionally focuses primarily on risk from a project management perspective, as expressed in the potential for cost overruns or progression delays in construction projects. Quality risk appears to be neglected in literature of risk assessment (Taroun, 2014). This was noted as early as by Williams (1995), who attributed the scarcity in quality risk research to a lack of common scale. As noted by Das and Chew (2011), the impact of cost overruns and delays can easily be measured, defects cannot. As a result, research into quality risk is generally qualitative in nature. An example of quality risk research into green roofs is the work of Wilkinson et al. (2015), who arranged interviews and expert meetings to identify technical risk aspects. An interesting conclusion of Wilkinson et al. is that there exists a general lack of understanding of technical issues related to green roofs.

Additionally, as outlined in section 1.6, comprehensive data on building defects is not easily available, a factor that makes quantitative risk analysis challenging. Without accurate or representative data on the frequency or impact of building defects, the application of quantitative risk modelling tools will not yield useful data. Note that any large and comprehensive data set on building defects, were it ever compiled, would have limits to its applicability outside of its original context because of variations in climate, the use of building materials/building solutions, and management culture. Conclusions drawn on the causes of building defects in a tropical country would not be immediately applicable in a cold-climate country like Norway. Quantitative risk assessment of building defects has been attempted (i.e. by Aljassmi et al., 2014, 2016; Aljassmi and Han, 2013), but their models were found to be of better use to describe the relations between conditions leading to defects than to make conclusions about the frequency of specific defects.

4. Methods

4.1 Scoping literature reviews

The purpose of the first part of the thesis was to chart available research literature on climate adaptation of buildings in general, and of blue-green roofs in particular. To achieve an overview of the state of the art, a literature search method known as a scoping study was found to be the most useful.

A scoping study, as described by Arksey and O'Malley (2005), is an approach to literature review which aims to map the extent of scientific research on a specific topic, through systematic searches in scientific databases. For a detailed description of the search procedure, see **Paper 1** and **Paper 2**.

The literature found in each scoping study was assigned various labels and categories, i.e. based on their main topic of study, charting which aspects of climate adaptation and green roof had received the most attention in literature. Sorting the literature by categories made it possible to identify knowledge gaps. In **Paper 2**, labels were used to chart the type, scale, and age of specific green roof assemblies studied in the articles.

4.2 Semi-structured interviews

The results of the literature studies were used to guide the rest of the research. As **Paper 2** found that research into green roofs on operational buildings was sparse, with no identified mentions of defects or quality risks, it was decided to focus on these aspects in the research going forward. While defect and quality risk data were not found concerning green roofs, much literature was found concerning compact roofs. Compact roofs serve as the foundation for modern green roofs, and for building technical purposes these layers are where defects occur. Compact roofs were thus included in the research to complement the scarce information found on green roofs.

To gather further data to steer the research, semi-structured interviews were arranged with actors in the Norwegian building sector (**Paper 3** and **Paper 5**). The aim was to create a qualitative picture of the general characteristics of roof defects as seen from different perspectives of the building sector. 7 individuals representing five different organizations were interviewed. The represented organizations included two public property developers, an insurance company, a material supplier, and a governmental advisory body. The individuals all had many years of experience in construction or material science. While the body of interviewees was regrettably not large enough to draw any quantitative conclusions, qualitative descriptions of the characteristics and prevalence of roof defects could be gathered.

4.3 Document studies

4.3.1 Green roof tender documents

This part of the research focused on the procurement of green roofs from the perspective of building owners (**Paper 3**). The transition between the pre-design and design phases of a building project is often where a contractor enters the project, through the initiation of a design-build contract. The contractor will then be responsible for designing and constructing the building as instructed by the building owner. The nature of these instructions is of great interest for green roofs, as they determine many of the premises for the roof's design and construction.

Pre-design documents for seven projects involving green roofs were obtained by reaching out to public building owners and by searching the Norwegian national public tender database, Doffin (2019). Focusing on the public sector had the advantage of assessing projects where the initiating party is likely to own and operate the building throughout its lifespan, as opposed to private actors who may seek to sell the building when it is finished. Private actors may thus not carry any quality risk in the project beyond the point of handover, which affects their approach to quality risk management in the early phase.

Technical pre-design reports were available for four of these projects. The levels of specification provided for the green roof in these projects were studied and compared. Also noted were the reasons given for including a green roof in the projects, if any could be found.

4.3.2 Product datasheets and product standards

Common to all process-induced building defects is that the operating limits – design parameters or situations of use – of one or more materials are exceeded. The material supplier will seek to avoid responsibility for such building defects by legally declaring the operating limits of their products. A qualitative study was conducted on the presentation of these declarations and their relations to quality risk, by examining the product datasheets and user instructions of roof membranes, insulation materials, and drainage boards used in green roof constructions (**Paper 3**). The applicability of the documented information in a quality risk management situation was also assessed. While quantitative results of this research phase were scarce, it helped achieve an understanding of how quality risk is managed by material suppliers.

4.3.3 SINTEF Building Research Design Guides

This part of the research process investigated the SINTEF Building Research Design Guides, which serve as a primary component of quality risk management on the design stage of buildings in Norway (**Paper 4**). A case was constructed wherein the Design Guides would be used to aid the design of a blue-green roof on a non-ventilated roof structure. Blue-green roofs are a novel building element that is not explicitly covered by a dedicated design guide, but whose principles of construction can be extracted from existing design guides. An assessment of the list of Design Guides found that nine Guides were relevant to this use case. All individual recommendations in the main body of text in the nine Guides were extracted, sorted, and counted, this formed a basis for the quality risk reduction framework presented in **Paper 5**.

The large volume of identified recommendations in the design guides (977 recommendations compiled from 337 paragraphs of text) inspired a secondary phase of this research. Literature on cognitive science was investigated, and a psychology scholar was contacted, to identify a limit to the amount of information the human brain is capable to process with an adequate degree of reliability. No case studies were found that directly discussed the specific issue of information overload in engineering guidelines, but information could be extracted from related research.

4.4 Risk reduction framework

The risk reduction framework (**Paper 5**) was developed partially as a continuation of the work of Skjeldrum and Kvande (2017), whose paper provided some early specifications and content for a risk reduction framework for blue-green roofs. The development of the risk reduction framework has also been inspired by the development of other similar frameworks within the Klima 2050 consortium. The most comparable examples are the framework for procurement of climate-adapted buildings (Sivertsen et al., 2019) and the framework for unearthing of rivers (Sivertsen et al., 2021). Common to both frameworks are a focus on the accessibility of information, the use of check lists for each actor and project phase, and the organization of project participants and their responsibilities. Knowledge and experiences from the development of frameworks in Klima 2050 has been used in the development of the risk reduction framework for blue-green roofs.

An article by Grynning et al. (2020) formalizes requirements for a climate adaptation framework for maintenance, operations, and management (MOM) of buildings. Grynning et al. also establishes four criteria for a framework to meet, which can be summarized in general terms:

- Compliance with national standards
- Compliance with ISO standards and established methods of risk assessment
- Being generic and applicable at all scales and for all relevant actors
- Being specifically applicable in a national context, taking into account previous work from national research groups.

The work also takes inspiration from the Norwegian national standard for moisture-safe buildings (Standards Norway, 2020), primarily in the aspects of organization, involvement, and responsibilities of project participants, and the procedures used to . The concept of distilling the complex requirements of a blue-green roof into ten overarching categories was inspired by Asphaug et al. (2020), who conducted this exercise for basement envelopes.

4.5 Expert and thematic meetings

Thematic expert meetings were arranged at several occasions throughout the PhD work. Actors from the Klima 2050 consortium (and occasionally, other invited experts), representing the entire value chain of the Norwegian building sector, were gathered in meetings to discuss various issues on a multidisciplinary level. One such expert meeting was arranged specifically for the writing of **Paper 5**, with the purpose of evaluating and improving the core matrix of the proposed quality risk reduction framework. Additionally, many experts meeting have been arranged without being specifically pertaining to research for this thesis, but relevant lessons have still been learned from them. Minutes of the meetings are published as notes internally in Klima 2050. This thesis incorporates content from the following expert meetings and their minutes:

- *Temasamling | Grønne tak som møter bakken* [Thematic meeting | Green roofs-ground transitions]. Klima 2050 Note 41, Oslo, 2017 (Andenæs, 2017)
- *Temasamling | Ombygging blågrønne tak* [Thematic meeting | Retrofitting conventional roofs into blue-green roofs]. Klima 2050 Note 47, Trondheim, 2018 (Andenæs, 2018)
- *Temasamling | Blågrønt tak på R5 Regjeringskvartalet* [Thematic meeting | Blue-green roof on the Government Quarter building 5]. Klima 2050 Note 73, Oslo 2019. (Andenæs, 2019)
- *Temasamling | Overvannshåndtering* [Thematic meeting | Stormwater management]. Klima 2050 Note 74, Trondheim 2019 (Kvande and Muthanna, 2019)
- *Temasamling | Klima 2050 Rammeverk for klimatilpassa bygning* [Thematic meeting | Klima 2050 framework for climate-adapted buildings]. Klima 2050 Note 76, Trondheim 2019 (Time, 2019)
- *Thematic meeting | Use of grey-green solutions for rooftops, permeable pavements and rain gardens to manage stormwater at ZEB Laboratory.* Klima 2050 Note 101. Trondheim 2020 (Helness and Sivertsen, 2020)

- *Temasamling | Fordrøyende tak og utvendig taknedløp - hvorfor er ikke det helt rett fram?* [Thematic meeting | Runoff-delaying roofs and external downpipes ‐ why is this not straightforward?] Klima 2050 Note 111. Trondheim 2020 (Kvande and Bunkholt, 2020)

5. Main findings

5.1 Motivation, state of the art

The first phase of the research included reviews of existing research literature on climate adaptation and green roofs. It was found that the research into climate adaptation and green roofs is voluminous and varied, but knowledge gaps are evident in the literature.

5.1.1 Climate adaptation of buildings

Paper 1 investigated literature on climate adaptation of buildings in general, limited to scientific articles published between 2013 and 2018. The identified material – 68 scientific articles - was sorted into nine categories by topic. This sorting revealed topical trends in the research: articles concerning building envelopes comprised about one third of the material. Overheating, thermal comfort, and the health effects thereof comprised another third. It could generally be observed that the bulk of the research material focused on temperature increase as the main climate parameter for which buildings must be adapted. Only five studies were identified that discuss precipitation and wind impact on buildings. In general, it appears that research tends to focus on adapting buildings to a warmer climate, but not to a wetter climate.

The literature was also sorted according to the primary research method employed in each article. Computer simulations stand out as the most prominent research method in the field, comprising more than half the identified studies (35/68). A further 12 studies were literature reviews, and 7 were based on interviews and surveys. Notably, of the 68 studies, only eight were found to be based on measurements and observations in a laboratory or in the field. The vast majority of climate adaptation studies on buildings are thus grounded in desktop studies. The review indicates a lack of studies wherein future climatic conditions are used as the basis for laboratory experiments or field measurements. This suggests that building climate adaptation studies rarely use approaches where predicted scenarios are tested in practice.

In conclusion, **Paper 1** illustrates three notable knowledge gaps in literature on climate change adaptation: studies focusing on parameters other than temperature are scarce, there is a lack of research relevant to cold-climate countries, and practical measurements and solutions are uncommon.

5.1.2 Green and blue-green roof research

Paper 2 fills some of the knowledge gap of **Paper 1** by presenting a narrower review of adaptation measures for wetter climates – blue-green roofs – with a focus on cold-climate countries. However, as the term "blue-green roofs" is scarce in international research literature, most of the gained information from the literature review concerns green roofs. The results from **Paper 2** align with those of **Paper 1** in some cases and differ in others. Many of the investigated studies conducted practical research on various aspects of green roofs, albeit mostly on a small scale. A trend of focusing on warm-climate conditions is evident, but considering that heat is a bigger concern than cold in most of the world's countries, this is only to be expected. Perhaps foremost, a large volume of literature was found on the need to adapt buildings to address overheating, and the role of green roofs in cooling down a building. While this is a concern to some degree in Norway, even in locations north of the Arctic circle (Haase et al., 2013), green roofs are generally not considered or used as an energy savings measure in Norway. It was also conjectured that due to strict insulation requirements, Norwegian roofs are generally so heavily insulated that changes in roof surface temperature have little impact on indoor air temperature – however, in-depth studies of this issue were not identified.

However, recent research from Sweden directly responds to **Paper 2** with a study on the thermal properties of a semi-intensive green roof on a well-insulated building in northern Sweden. The results of the study largely agree with the conjecture of **Paper 2**, stating that the energy benefit of a green roof under these circumstances is low (Schade et al., 2021).

Green roof research in literature was found to overwhelmingly be conducted using small-scale test beds or temporarily installed roof plots, often with the purpose of investigating one aspect of their properties, such as their ability to retain water, their thermal behaviour, or the growth of particular plants under particular conditions. Scientific literature on the practical considerations of blue-green roofs was found to be sparse. There is a dearth of research into green roofs designed for decades of operation with realistic levels of maintenance. In all but three cases, the roofs subject to physical research were less than two years old at the onset of the research period. No research was found concerning green roofs at the end of their operational service life.

The lack of research on full-scale green roofs in their operational stage is understandable when considering the logistical challenges, but nevertheless present an interesting knowledge gap. A total picture of green roof design, construction, and operation appears to be missing from research literature to date.

5.2 Current approach and challenges

5.2.1 Norwegian legislation

Certain challenges to the current system of quality risk management were identified on the legislation stage. An example relevant to blue-green roof is how roofs should be designed to address precipitation. Stormwater management on rooftops is a novel feature in Norway. It is evident that certain edge cases introduced by blue-green roofs is not adequately covered by existing legislation. The legislation largely treats building requirements and stormwater management as separate issues to be addressed by separate disciplines with different areas of responsibility. The subject of runoff water from roofs interfaces with both disciplines. Their separate approaches to roof runoff illustrate that the two disciplines have very different perceptions of what is the main challenge to be addressed.

An interesting case of an inter-disciplinary conflict of interests was found in the Norwegian legislation. The Technical Regulations (DiBK, 2017), §13-12(2) states: "*Roofs must be designed with sufficient sloping and drains, so that rain and snowmelt run off. Precipitation, snowmelt, and icing must not cause damage to the building*" (author's translation). The focus is to preserve the integrity of the roof, by efficiently removing precipitation water before it compromises the roofing materials. The VTEK text of the same paragraph presents a pre-accepted solution for compact roofs: "*For non-ventilated roofs (compact roofs), snowmelt must be led from colder to warmer areas of the roof* [author's note: to prevent it from re-freezing] *and drained away in frost-free drainpipes without the use of heating coils*" (author's translation). The conventional, solution to achieve frost-free drainage is to connect the roof drains to downpipes running through the heated parts of the building (internal drains), that connect to the local stormwater pipes at frost-free depths underground. This solution is considered the default way to drain compact roofs in the SINTEF Building Research Design Guides, whose design guide for compact roofs (Noreng, 2018) states as a main rule: "*Compact roofs should have internal drains*". The design guide for external roof gutters and drainpipes (Larsen, 2017) does not mention compact roofs, further reinforcing the idea that compact roofs are drained internally by default.

However, internal drainage is not desirable from a stormwater management perspective. The perceived main challenge of roof water from this perspective is that large quantities of roof runoff contribute to overloading stormwater systems. Legislation on stormwater management reflects this perception. There is an increasing tendency to require roof downpipes to be disconnected from the stormwater network, leading the roof water out onto open terrain for local infiltration. In TEK17, §15-8 (1) states: "*To the greatest possible degree, stormwater and drainage water must be infiltrated or otherwise handled locally to secure the water balance in the area and avoid overwhelming the sewage management plants*" (author's translation). VTEK clarifies: "*The purpose of the provision is to avoid that stormwater is led to the main stormwater pipe and ensure that stormwater is managed locally"* (author's translation). Local regulations for stormwater management have gone further in expressing the need for roof water to be disconnected from the stormwater system and instead led onto open terrain. This is explicitly stated as a requirement in the local legislation of several Norwegian municipalities (Opheimsbakken et al., 2017; Oslo Municipality, 2017; Ringerike Municipality, 2018).

However, with external drainage of roof runoff, frost becomes a concern. The heat flux through a compact roof may melt snow even when the ambient air temperature is below the freezing point. Under these conditions, snowmelt will re-freeze when it drains away from the "warm" roof and into unheated gutters and drainpipes. The subsequent ice accumulation can create ice dams or icicles, and cause damage to building components. This challenge has been treated in a supplementary article to this thesis (Andenæs et al., 2020). External drainage from compact roofs is considered an unconventional solution from a building technical standpoint. The SINTEF Building Research Design Guides mention it as an alternative solution that may be feasible in coastal climates (Noreng, 2018; Noreng and Krohn, 2007), but no design recommendations are presented for this solution in the design guides.

A duality of philosophies is evident in the legislation. The discipline of building science prioritises to drain water quickly and efficiently off the roof, with a focus on frost protection, but without general concern for issues downstream of the roof drains. The discipline of stormwater management prioritises these downstream issues but does not consider the building technical challenges of the roof. The favoured default solution of either discipline is considered unfavourable or problematic by the other.

5.2.2 Risk perception

The document studies show that quality risk management is approached differently by different actors in the building sector, causing certain quality risk aspects to be overlooked. Each actor seeks to reduce risk in their area of responsibility, in theory ensuring risk management in every part of the building project. However, there does not seem to exist any unifying framework to coordinate the management of quality risks, nor is there a clear delegation of responsibility for edge cases and interfacing disciplines. Each actor generally seeks to reduce risks in terms of having to pay for repairing a building defect. This can be achieved in two ways: working to reduce the number of defects or working to reduce one's own responsibility for the effects that occur.

In the end, the building owner appears to be the actor with the greatest likelihood of having to pay the costs of defects (either through repairs or through reduced building quality), and consequently the actor carrying the greatest quality risk. However, the approach to managing quality risk by building owners in the early phases of a project was found to be inconsistent. Some of the examined building tenders provided no specification for the planned green roof beyond “A green roof is to be installed”, essentially leaving its design and installation to the main contractor in a design-build scheme. Others gave more detailed specifications, but the variation between projects was significant. Quality risk management in this phase appears to hinge mostly on the judgements of the individuals involved, signifying the need for a systematic approach so that a best practice can be shared and widely adopted.

5.2.3 Perception of guideline information

The assessment of the SINTEF Building Research Design Guides revealed an interesting gap in the approach these guidelines take for managing quality risk. The design guides document pre-accepted solutions and list primary concerns and recommendations for the individual building parts. They are widely used and trusted in the Norwegian building sector, to the point of being used as a source of reference by TEK17 (DiBK, 2017).

Seen in isolation, the design guides serve as a measure to reduce quality risk by describing solutions for building details that meet the legislative requirements. However, it was found that aspects of their implementation might carry an inherent risk that hitherto has received little attention. The challenges to their use are varied, and exist on at least three levels:

1. The process of extracting relevant knowledge from the sum of several design guides is complex, and there is no super-level guidance to aid it.
2. The challenges involved in blue-green roofs as described in the design guides exist over the full timeline of the building’s life span, from conception to the use phase.
3. Blue-green roofs are erected in the concurrence between several crafts and disciplines, involving challenges related to water management, structural mechanics, thermal insulation, landscape architecture, waterproofing, and several others.

The volume of information presented in the design guides spurred the question of how much information is too much. With some help from a psychology researcher known to the author, scientific literature about information perception and information overload was retrieved and studied. Findings suggest that the upper limit of the number of data points the human brain could effectively process at the same time is around 100-200 (Falschlunger et al., 2016). No studies were found that directly discussed engineering guidelines, but lessons from studies of information perception suggest that the limitations of the human brain should be considered when presenting information that could be critical to a project.

Current quality risk management appears to place great trust in information being followed as long as it is available. There appears to be an assumption that information will be applied to the project by the relevant actors if they are aware of its existence, although this may not be feasible in practice. For instance, the operational limitations of a specific product may be cited with reference to dozens of standardized test methods, whose content require a subscription to access and whose limitations may not be apparent to actors without prior expertise with the relevant type of product. Evaluating the suitability of the product in an individual project may not be feasible without a more detailed analysis than what time or budget allows, considering the multitude of different products used in a building project.

To some degree, this can be observed in the SINTEF Building Research Design Guides as well. Information is presented without any overarching principles or guidelines about the main challenges to be resolved.

While the advice presented in the design guides is valid and helpful for a specific purpose, the complexity inherent in the structure of the guideline series prevents it from serving as a complete quality risk management tool on its own. Stratification of the material – creating a hierarchy of main concerns – or simplification would greatly complement the existing guidelines and make users more aware of which information to seek out and prioritize.

The practical results of information being poorly structured are evident in the studies focusing on specific construction projects. As seen in the study on construction tenders in public databases (Andenæs, Time, et al., 2019a), the degree to which public property owners detail their specification documents vary greatly and appear to depend on the thoroughness of the individual authors of pre-design reports. Awareness of common defect mechanisms and measures to prevent them seems inconsistent. Even though a post-assembly watertightness test is recommended in guidelines on compact roofs (Noreng, 2008, 2018), it appears to rarely be carried out in practice.

The defects observed in case studies (**Paper 5**) all include fault mechanisms that were previously known in building science, such as the intrusion of indoor moisture through perforations in a compact roof (Hutchinson, 2017), or roof collapse due to a blocked drain (Wilden and Syed, 2020). The defects that have been observed could all be prevented by following known design and construction principles, suggesting a lack of awareness by one or multiple actors in the construction process. It is evident that measures to reduce quality risk need to focus not only on providing advice on a detail level, but also take measures to ensure that advice can be processed and understood effectively.

5.3 Suggestions for quality risk assessment

This part of the thesis seeks to process the findings from part 1 and 2 and propose a framework to reduce quality risks associated with blue-green roofs. It has been found that existing guidelines cover the details of blue-green roofs comprehensively, although an overview perspective appears to be missing. Identified building defects in case studies all originate in issues that were covered by existing guideline literature. The overall challenge in terms of quality risk is not a lack of information on how roofs should be built, but that the information is not applied.

5.3.1 Requirements of a quality risk framework

A quality risk framework should not just seek to provide technical information but also focus on making it understandable. The framework needs to be symbiotic with the SINTEF Building Research Design Guides rather than replacing it. While the design guides concern how to address the various issues on a detail level, the framework should address challenges on a more general level and make the user aware of which issues must be addressed in a blue-green roof project.

The risk reduction framework should ideally present its information in such a simple way that anybody involved in the project could obtain an overview of the common risk factors for the roof assembly. Awareness of technical challenges is the key to their solution.

5.3.2 Structure of the framework

Details of a blue-green roof that are prone to water intrusion are shown in Figure 11. These details are treated separately in the current design guides; some in separate documents that do not mention green roofs at all. A proposed improvement includes a design guide or supplementing document that lists overall points of concern for a blue-green roof and where to find further information, including a listing of special details. It would also guide design reviews and on-site inspections on where to direct particular attention.

Constructability of these details is another crucial factor, as the risk of construction defects increases if the detail is not easy to build. As an example, the overflow drain seen penetrating the parapet on Figure 11 is arguably placed too low and close to the level of the roof, making it difficult to properly fit a waterproofing sleeve around the pipe.

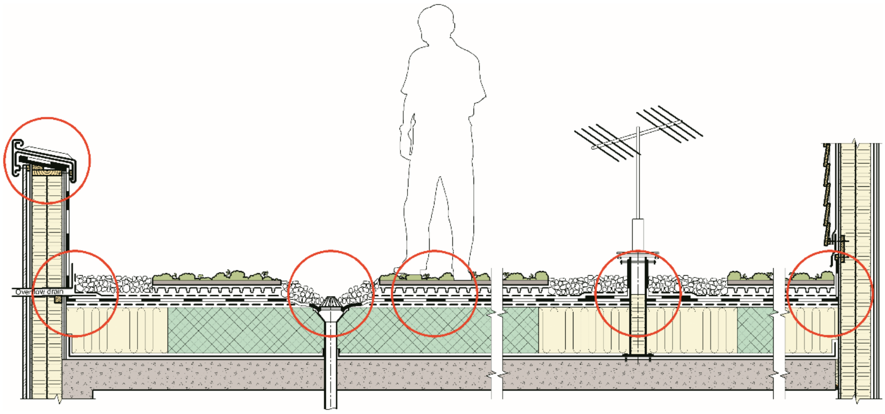

Figure 11: Points on a blue-green roof susceptible to water intrusion. From left to right: Flashings at the top of parapets, transitions between roof and parapet, drain, areas of high traffic, mounting brackets for technical equipment, and transitions between roof and adjoining walls (including doors). Illustration: Klima 2050/SINTEF.

To address the main risks associated with green and blue-green roofs, a risk reduction framework is proposed. Technical challenges are sorted according to categories based on their main discipline, and according to the project phase where the relevant decisions are made. The aim is to present main concerns and recommendations in a simplified fashion, so that it can be processed and understood by decisionmakers in the project regardless of their main discipline specialization. An outline of the matrix of the risk reduction framework, attached as the appendix to **Paper 5**, is presented in Figure 12.

Categories / Project phase	Concept	Pre-design	Design	Construction	Use
Blue-green functionality	• Evaluate ... • Etc. • ...	• Determine ... • Etc. • ...	• Select ...	• Schedule ...	• Establish ...
Organization	• Assess ...	• Involve ...	• Verify ...	• Inspect ...	• Review ...
Material integrity	• Estimate ...	• Determine ...	• Choose ...	• Perform ...	• Assess ...
Moisture-proof design	• Assess ...	• Identify ...	• Review ...	• Control ...	• Inspect ...
Drainage and drains	• Estimate ...	• Identify ...	• Develop ...	• Control ...	• Control ...
Structural loads and wind	• Estimate ...	• Identify ...	• Determine ...	• Avoid ...	• Evaluate ...
Fire protection	• Assess ...	• Define ...	• Define ...	• Perform ...	• Remove ...
Maintenance	• Estimate ...	• Establish ...	• Detail ...	• Document ...	• Follow ...
Environmental issues	• Define ...	• Assess ...	• Demand ...	• Ensure ...	• Avoid ...

*Figure 12: Outline of the risk reduction framework presented in **Paper 5**. Note that the complete matrix has multiple bullet points in each cell. Illustration: Klima 2050/SINTEF.*

It should be noted that information perception is a separate field of study within cognitive science, which normally interacts little with engineering disciplines. Cooperation between the disciplines may not be easy to arrange, especially in industry settings. However, using expertise in cognitive science may be of great benefit when designing guidelines intended for a broad and multi-disciplinary audience. Further development of the risk reduction framework should seek a better understanding of this expertise, through more in-depth studies or cooperation with cognitive researchers.

5.3.3 Implementation of the framework

There are several possible approaches to using the framework in a real project. How the framework will be used depends on many variables/decisions, e.g. the degree of involvement of actors in each stage, ownership of responsibility to ensure the framework is followed, and the contractual formality in following the "checklist". The implementation will be greatly affected by the choice of project delivery model as the model dictates everything from responsibilities and influences to the point of involvement for every actor.

An example way to implement the framework involves a collaborative delivery model (Engebø et al., 2020). As the framework spans multiple project phases, not all decision-makers will be involved in every piece of the framework. However, with the client having the overall responsibility for the project, it is natural that they initiate the use of the framework and introduce it to the project. This may be done already in the procurement policy through using proper selection criteria's for evaluating and selecting an actor to execute the project. More specifically, the client could opt for a qualification-based selection where familiarity with, or acknowledgement of, the framework is to be weighted. From there, the client could include the framework in documents associated with the procurement process – either through the contract or through a non-contractual document such as an so-called ambition note (see for example Time et al. (2019)).

Regardless, the main purpose for the framework should be to serve as a checklist for all the actors who, either directly or indirectly, have an interface towards the blue-green roof. As an example, the designer should provide the contractor with relevant information for the execution of the construction, and also communicate with the service personnel responsible for the maintenance. Approaches vary in terms of how formalized the use of the framework should be, varying on a spectrum between using the framework loosely as a planning aid during the process, and the client requiring documentation to verify that the framework is followed. This level of ambition must be clarified with the other participants.

Several incentives may be used to agree on how the project will use the framework. The lowest level of incentive is the use of workshops where project participants discuss the main points of the framework. Workshops may be arranged in an early project phase or at the onset of each phase. The middle level is to enshrine the framework as part of the ambition document for the project, for instance in the tender documents for a design-build contract. Its use will thus be codified in the body of documents on which the project is based. The highest level of incentive is for the client to set up a construction contract where the scope of the framework and responsibilities associated with it are defined and legally bound.

One limitation of the framework in its current form is that the recommendations vary in terms of how strictly they should be enforced. Some checklist items concern the conceptual approach to the project or its organization – e.g. “establishing lines of communication between disciplines” – while others are more specific and need to be grounded in contracts – e.g. “Performing watertightness test before the assembly of blue-green layers”. These variations should be addressed in future versions of the framework, adding guidelines to make it easier to determine and assign responsibilities for meeting its recommendations.

6. Conclusions

This thesis has explored blue-green roofs and their associated risks through three main disciplines: Building materials/physics, hydrology, and project/risk management. The three main phases of research have been 1) the collection of multidisciplinary research data from literature, 2) mapping the perceptions and management of quality risk in the Norwegian building sector, and 3) Proposals of how to structure and coordinate quality risk management through a multidisciplinary framework.

Knowledge gaps in relevant scientific disciplines have been identified. The impact of increased precipitation on buildings as a result of climate change is little studied. In general, there is evident a tendency to focus on increasing temperature when discussing climate adaptation of buildings – an observation which is to be expected, considering that this is a primary concern in most of the world's countries. Moreover, the research is dominated by computer simulations and desktop studies, with a general lack of studies featuring physical measurements. Likewise, similar trends are exhibited in green roof research: while there exist many studies featuring physical measurements, and many on precipitation, cold-climate concerns are generally under-studied. Research featuring physical measurements on full-scale green roofs in operation, hereunder green roof defects, are also found to be scarce.

Current quality risk management practice in the Norwegian building sector is fragmented and largely dependent on the individual actor. Systematic guidelines to assess or manage quality risk have not been found. The SINTEF Building Research Design Guides is a widely trusted and consistently updated source of technical recommendations, but challenges exist with its overall structuring of information. While comprehensive data on building defects is not available, qualitative assessment of defect cases suggests that it is overwhelmingly rare for the primary causes of defects not to be addressed in one form or another by existing guideline literature. The overall challenge of quality risk management does not appear to be a lack of technical information, but that the information is not applied. It is conjectured that the difficulty of processing large quantities of information is a primary reason for this general deficiency.

To this end, a quality risk reduction framework is presented. It is designed to cover the most important quality risk concerns of blue-green roofs, structured to sort the information to be accessible and understandable. The framework is designed to be symbiotic with currently existing guidelines, rather than acting as a stand-alone document to replace existing literature.

7. Further work

Paper 5 in this thesis presents a proposed framework for managing quality risk in blue-green roofs. The further development, presentation, and implementation of this framework is the most notable work to be conducted in the continuation of this thesis.

Crucial to this development is the structuring and organization of information to make it accessible to decisionmakers in a building project. It is shown that current practice of guidelines has large potential for improvement. However, the subject of information sharing in engineering projects appears to be little studied and involves scientific disciplines that have been little involved in engineering to date. Future guidelines may benefit greatly from a multi-disciplinary approach involving cognitive science to ensure that presented information is understandable to the end user and useful in a practical setting.

One common feature of this thesis has been the use of qualitative data in the research. In many cases, quantitative data has not been available for study. This has also made quantitative risk analysis a futile task. However, given sufficient data, quantitative assessment of quality risk would be of great help to determine focus points for further reduction of the number of building defects.

A comprehensive compilation of data on building defects would be essential for understanding the causes and consequences of building defects. With sufficient data to form a representative data set, quantitative analysis of building defects in Norway may also be performed. The Norwegian Building Authority has a mandate to create a common Norwegian building defect database, but the database has yet to be concretized as of this writing.

More quantitative research on green and blue-green roofs may also be conducted as their numbers increase in Norway. The process of aging should be investigated to identify the degradation rate of green roof materials. In particular, there is great interest in determining to what degree the life of a roof membrane can be prolonged by the protection of green layers. Defects, damages, and end-of-life conditions at operational green roofs should also be studied. However, at present in Norway, modern green roofs have not been in use for long enough to reach the end of a natural lifespan. No defect cases involving modern green roofs in Norway are currently known. It is the hope of the author that this status will be retained even as more green roofs are built in the future.

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Paper 1

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Review

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Abstract: As the climate changes globally and locally, the built environment will be subject to different climatic exposure than in the past. Adaptation measures are required to ensure the long-term integrity and successful operation of the built environment. This study examines literature on climate adaptation measures for buildings through a scoping literature review. It is centered around the main journals in the field of climate adaptation of the built environment, then expanded to map the extent of scientific publications about climate adaptation in general. Studies that regard future climate scenarios have been of particular interest. The majority of the identified literature concerns climate change impacts on buildings in warm climates, with overheating being seen as the greatest challenge. Additionally, few empirical studies are found; most identified research is based on computer simulations or literature reviews. The volume of research on the consequences of climate change on buildings in cold regions is surprisingly small, considering the pecuniary stakes involved. The predictions of climate scenarios suggest regulatory/policy measures on climate adaptation should be taken as quickly as possible to avoid greater costs in the future. However, further research into future scenarios is also essential.

Keywords: climate change; adaptation measures; impact; buildings

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1. Introduction

The global climate is a complex system in constant fluctuation. Data collected over the recent decades, shows that it is currently changing unusually rapidly in a historic context. The likely primary cause is found to be anthropogenic activities. Increased concentrations of greenhouse gases in the atmosphere capture more thermal energy, causing the global average temperature to rise (global warming), which greatly influences the atmospheric climate [1]. This temperature increase causes, among other things, shifts in weather patterns and sea level rise. Climate change will have severe consequences for a built environment designed under the assumption of steady conditions.

The so-called Representative Concentration Pathways (RCPs) describe radiative forcing from greenhouse gas concentrations in the atmosphere for future climate scenarios. The RCP projections are used to predict consequences of climate change [2]. The four RCPs used for climate modelling as defined in the IPCC fifth assessment report are RCP2.6, RCP4.5, RCP6, and RCP8.5, here shown in increasing order of severity [3].

The impacts of climate change differ between different regions. In hot climates, the main challenges for the built environment are drought and overheating. In coastal cold climates, overheating is not likely to present a problem for buildings, but a milder climate brings challenges as well. Norway is an example of such a region where climate change is expected to bring higher average temperatures year-round and increased levels of precipitation. The national average air temperature in Norway has risen by 1 °C between 1900 and 2014, and precipitation has increased by 18% over the same period [4]. The trends are expected to continue over the next century. Among the most notable consequences are shorter and milder winters, as well as more frequent and intense rainfall events. Sea level rise is a relatively minor concern in Norway, as it is largely counteracted by land rise [4]. However, increased precipitation in the form of intense rainstorms is expected to lead to costly damages to buildings and infrastructure by 2100 [5].

Evaluation of adaptation measures for buildings is therefore of high importance. To assist future research, and to find conclusions from previous studies, it is necessary to map the extent of scientific publications on climate adaptation. The purpose of this study has not been to review the investigated articles in-depth, but rather to acquire an overview of the available literature. The subjects, research methods, and main findings of articles concerning climate adaptation of buildings has been mapped to provide an overview of the extent of scientific studies in this field of research. This overview will then be used as a basis for future research into climate adaptation of buildings.

To examine this matter, the following research questions are addressed:

- What is known from existing literature about climate implication and adaptation measures for buildings?
- What are the most important research gaps?

The first of these research questions will mainly be addressed by the Results section (Section 3), where literature findings are summarized, while the second is addressed in the Discussions section (Section 4). The results presented in this article form part of a larger literature study which concerns climate implication and adaptation measures. Since the study resulted in a volume of literature too great to present in a single paper, it was decided to divide the results into two parts. One part concerns the aspect of energy use in buildings and was presented in [6]. The other part, which concerns climate change implication and adaptation measures for buildings in general, is presented in this article.

2. Methodology

This study is based on findings from a scoping literature review, carried out between November 2018 and January 2019. A scoping study typically aims to "map rapidly the key concepts underpinning a research area and the main sources and types of evidence available and can be undertaken as stand-alone projects in their own right" [7]. A scoping study is also helpful to map the extent of the material published in a given scientific field, in order to analyze its research trends and uncover knowledge gaps. This study aims to conduct such an analysis. The primary goal is not to review all the existing literature in depth, but to map its extent. The results can then be used to focus and direct future research by addressing the knowledge gaps or by conducting more thorough reviews of narrower selections of studies.

The objective for this study was to map scientific literature about climate change impacts and adaptation measures for buildings. Its main purpose is categorizing and analyzing the findings as defined by the listed research questions. The method was based on the framework described by Arksey and O'Malley [7]. This involves a six-step procedure: (1) Identifying the research question; (2) identifying relevant studies; (3) study selection; (4) charting data; (5) collating, summarizing, and reporting the results; and (6) consultation. The procedure is also used to identify the research gaps. The study presents a thorough and valid method for mapping the research field, to discover the measure and the characteristics of the research done on the subject [8].

Given the extent of the material identified, certain limitations had to be outlined. The scope of the research mainly concerns questions of building physics. As such, articles concerning urban and spatial planning, infrastructure, governance, as well as energy use in buildings, were excluded. Articles which concern climate change and buildings, but where the impact of climate change on buildings and adaptation measures is not the main focus, were discharged.

Furthermore, as according to the guidelines provided by Arksey and O'Malley [7], the research quality of the articles included in the review was not assessed in depth. However, considering the increasing problem of predatory journals without any sort of peer review, it is still necessary to assess the overall scientific legitimacy of each article and its origin. The practical research procedure is illustrated in Figure 1.

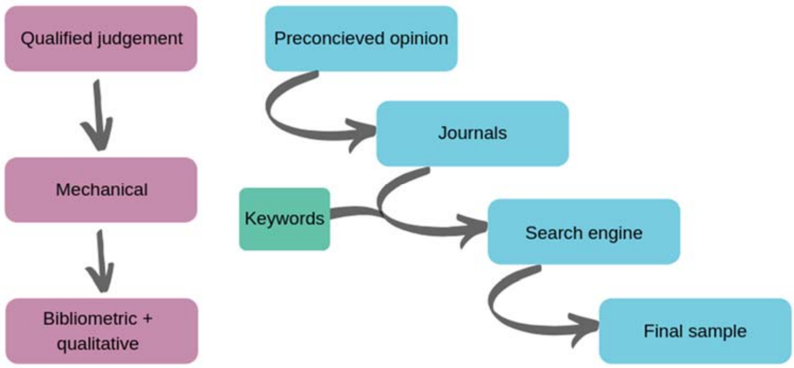

Figure 1. The selection of articles for the study is illustrated on the right, while the left column shows the evolution of the procedural rigidity as the study developed.

2.1. Identifying and Selecting Studies

To successfully identify the greatest portion of the relevant literature in a field, multiple databases should be involved in the literature search [7]. This study encountered a large extent of the available literature; thus, two main search processes were used to sort through the material. First, hand-searching of selected key journals as described in Section 2.2. Second, a more focused search was conducted in selected databases and search engines.

In total, more than 20,000 article titles and/or abstracts were examined in order to identify studies related to climate implications and adaptation measures for buildings. One hundred and sixty-three articles were identified and included for further analysis. Due to the volume of results being too great to comprehensively present in a single study, it was decided to split the work into two separate studies. This study presents a set of 68 articles regarding the topic of implications and measures for buildings, excluding articles concerning energy use in buildings. The topic of energy use, spanning 67 of the articles, is presented in an earlier work by the authors [6]. The remaining 28 articles were found to be outside the scope of either study and dismissed after the more thorough analysis of the content.

2.2. Hand-Searching of Key Journals to Sample the Field

To identify research relevant to the field of inquiry, recent volumes of key journals were hand-searched in the first part of the study. The purpose of this phase was to obtain an overview of the content and scope of key journals within the field, to use as a starting point to determine search phrases to use in the later phases of the literature study. Twelve key journals were selected for examination based on the experience of research co-workers and pre-conceived opinion. The 12 selected journals were: *Building and Environment*, *Climate Services*, *Energy and Buildings*, *Building Research & Information*, *Journal of Climate Change*, *Buildings*, *Journal of Building & Physics*, *Climate Sustainable Cities and Society*, *Energy Policy*, *International Journal of Climate Change Strategies and Management*, *Advances in Energy Building Research*, and *Construction and Building Materials*. The latter journal was later omitted from this search phase. Only publications of this journal from 2018 were examined, due to the extent of the content published in it (40 volumes for 2018 alone). Hand-searching its contents was found to be too laborious considering the time constraints. As no articles relevant to the study were identified among the 2018 volumes, the journal was discarded from further study in the hand-searching phase. It was decided to assume that any relevant articles published in this journal would be found through the database search later.

The search sought articles related to building science and/or climate change related issues, that were newer than 5 years old. The relevance of articles to the search was assessed through their titles, keywords and abstract. This phase of the search identified 74 relevant articles from the 11 studied journals, which were also used to determine search terms for the database study.

Identification of Search Terms

Keywords of the articles found in the first phase of the search were used to select search terms for the second phase. As shown in Figure 2, keywords in the selected articles were listed and counted. The most relevant keywords were determined based on frequency and qualitative judgment. This strategy creates a consistent basis for the final search phase as described in the following paragraph.

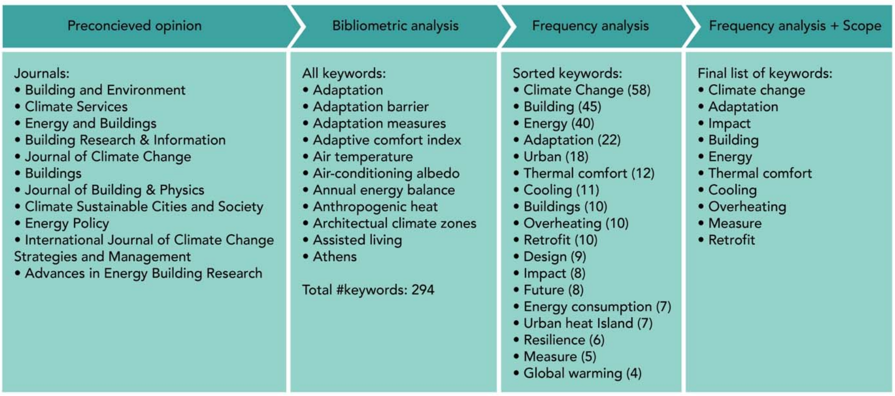

Figure 2. Procedure for identifying and selecting search terms for the database search.

2.3. *Search through Databases and Search Engines*

A systematic search was conducted using combinations of search terms selected as shown in Figure 2. Three databases were used for the search: Google Scholar, ScienceDirect and Oria (a Norwegian university library search engine). The strategy for the search is outlined in Table 1.

Table 1. Filters used for search through databases and search engines, filter explanation, and number of unique identified publications.

Search Engine	Filter	Filter Explanation	Unique Identified Publications (doubles)
Google Scholar	Title and topics	All field-search gave an unmanageable number of hits	2 (13)
Oria	Title	All field-search gave an unmanageable number of hits	36 (70)
ScienceDirect	Title, keywords and abstract	Search results could be examined manually	50 (65)

These electronic databases provide tools for narrowing the search and filtering out irrelevant results. The search was limited to scientific research and review articles published in English over the past five years (2013–2018). Documents such as patents and conference papers were excluded from the search. The databases have different options for filtering their output, so it was necessary with some variation in the search strategy for each database. The filters used for each of the databases are listed in Table 1. The table also lists an explanation for the filters and the numbers of unique and duplicate identified publications. Duplicate publications were not included in the final sample of articles. Regardless of the filters used, all search terms and term combinations were used consistently across all databases.

2.4. Sorting of Articles

The number of hits produced by the search created a need for an extensive screening. A three-step process was employed to find relevant articles from the results: Firstly, all articles whose titles clearly showed they did not relate to climate adaptation of buildings were excluded. If the title was found to be relevant, the abstract was examined. If the abstract was found relevant, the article was examined in detail.

2.5. Charting and Reporting the Results

After the screening process, all accepted articles were kept for analysis. This included a charting of the data, described by Arksey and O'Malley [7] as "a technique for synthesizing and interpreting qualitative data by sifting, charting, and sorting material according to key issue and themes". A database in the form of spreadsheets was created to aid in the analysis of data. The database collected the article's title, author(s), keywords, year of publication, study location, purpose, methodology, and highlights from the study.

The articles were then categorized, as illustrated by Corbin and Strauss [9]. Through a thorough analysis while categorizing, some articles were dismissed because of lack of relevance. The final sample consisted of 68 articles divided into nine categories: Building envelope, design tools for integrating climate projections, frameworks and guidelines, overheating, thermal comfort, health impact, precipitation and wind impact, sustainability and resilience, and policy. The category "building envelope" was divided further into three sub-categories (greening, material selection and design strategies). The categorization of the results is not discrete but intersect to a certain extent. There is significant overlap between several categories; for instance, health impact is often related to overheating, while overheating happens when the thermal comfort is unsatisfactory. Some articles included in this study mention energy use, without it being the primary focus. It was noted whether each article primarily discusses climate change impact, measures, or both, as well as whether the study includes future weather scenarios.

A few of the articles could fit in more than one category, and some articles were difficult to relate to a specific category. Nevertheless, after several screenings, thorough examination and discarding of a few irrelevant articles, it was possible to separate articles into distinct categories. Furthermore, it was rather challenging to stipulate a main method used in each article. Some of the articles have used more than one method for their research and it was often difficult to apprehend the actual used method. Hence, some of the methods are identified by the keywords, others by a thorough review of the article's method section.

The synthesis consists of a qualitative analysis of the final selection of articles. In the analysis, the results are described according to their categorization in the Results section, with the primary focus being to describe the research purpose and findings of each article. The Discussion section provides a synthesis of what is known about climate implication and climate adaptation measures for buildings, as well as the current knowledge gap in the research.

3. Results

3.1. General Overview of the Material

The scoping study method is assumed to provide a comprehensive collection of scientific literature on climate adaptation for buildings published in the past five years. Given the magnitude of data obtained, this study only reports briefly on each article. Instead, as shown in the Introduction section, the focus has been on analyzing the extent of the literature and its research trends. The results are organized around the nine categories as described in Section 2.5. In Figure 3 the articles are sorted according to these nine categories, and to whether the study includes future weather scenarios. Notably, articles about policy as well as frameworks and guidelines have not been found to consider future weather scenarios. This trend might be explained by the nature of the topics. Future weather scenarios are considered in a majority of articles in most of the other categories.

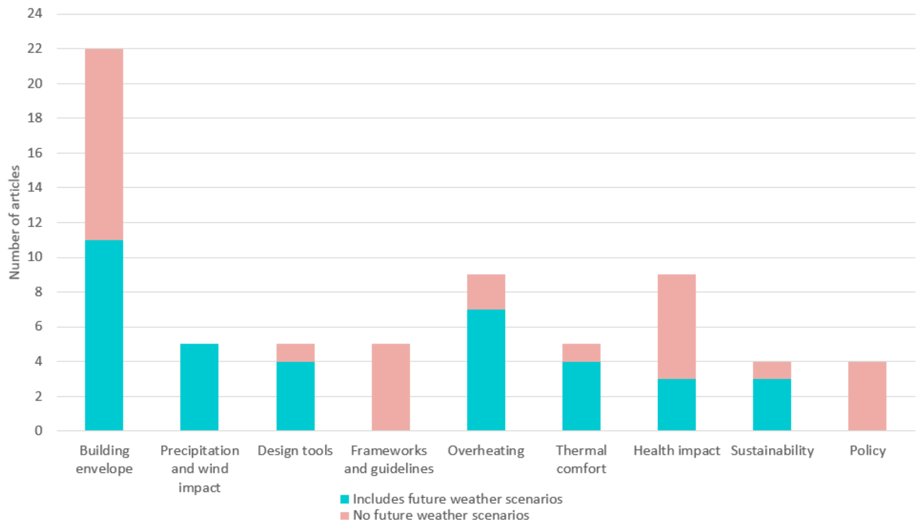

Figure 3. Number of articles sorted by topic categories and by whether the articles consider future weather scenarios.

The category "Building envelope" is sub-categorized into "Greening", "Material selection", and "Design strategies". Under "Greening", several ways of implementing green solutions as a climate adaptation measure on buildings are presented, while "Material selection" discusses the potential of different materials to encounter the changing climate. In the "Design strategies" section, possible approaches in the context of building design are offered. Studies concerning the impact of climate change on different weather factors, which involve rain, snow and wind load are categorized as "Precipitation and wind impact".

Further, the category "Design tools" explains tools for simplifying and integrating climate projections for building simulations. "Frameworks and guidelines" on the other hand, gives a brief summary of existing and suggested frameworks and guidelines for how to adapt buildings for the future climate. The combination of global rising temperatures and the urban heat island (UHI)-effect can, especially in big cities, cause severe problems with overheating. Articles treating this issue are gathered in the category "Overheating", while "Thermal comfort" addresses the impact of the rising outdoor temperatures has on indoor thermal conditions. How climate change—in particular, more frequent heat waves—lead to warmer indoor conditions and affects other aspects of the health of human beings, is treated in the category "Health impact". Different solutions and research on how to make buildings more sustainable, resilient and the optimal way to conserve old buildings in a changing climate are presented in "Sustainability and resilience". The industry's understanding of risks associated with climate change, barriers for implementation of climate change adaptations, and conceptual climate change adaptation strategies for project management are compiled in the category titled "Policy".

The literature in the field represents research from 22 countries across all inhabited continents. The UK research environment has however proved to be particularly productive. The yearly number of publications seems to be relatively constant; 10–15 articles were published each year the past five years. The journal *Building and Environment* is represented by the most articles.

The employed research method in each article is shown in Figure 4, as is whether future weather scenarios are applied in the study. Most of the studies that have utilized future climate scenarios have used data originating from global climate models (GCM) and downscaled them to regional climate models (RCM), which results in more appropriate weather files. A few have used already simulated projections, or rising temperature data based on the predictions in the concerned geographical area.

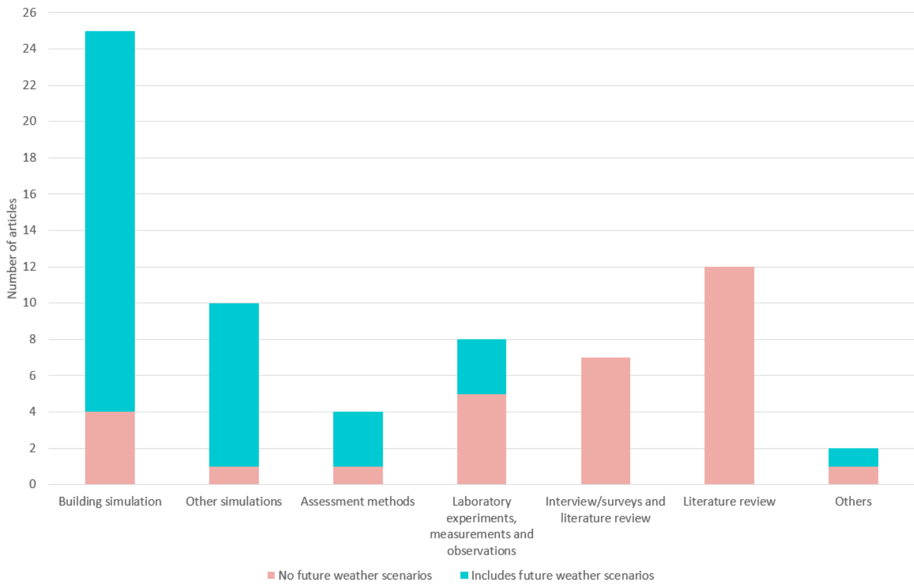

Figure 4. Number of articles sorted by their primary employed research method and by whether future climate scenarios were used for the analysis.

Future climate scenarios are notably absent from the categories eclipsing qualitative research methods, presumably because their inclusion is not applicable in the research design of such studies. All but a few studies conducting computer simulations took future weather scenarios into account, while this was significantly less common in laboratory studies.

As Figure 4 shows, the greatest number of the studies have reached their results through building simulation. This means that a building simulation tool, such as EnergyPlus or IDA ICE, has been utilized to simulate different factors like thermal comfort, the applicability of retrofit solutions and energy performance, the function of green roofs, or the building performance in general. The studies that have employed other types of simulations, such as spatial analysis, weather analysis, various physical models for urbanized areas (ex. SURFEX), dynamic downscaling models and Computational Fluid Dynamics models (CFD-models) are included in the section "Other simulations". Studies based on evaluation and weighting of different solutions, and decision analysis methodologies are gathered in "Assessment methods". Furthermore, "Laboratory experiments, measurements and observations" include research based on recorded climate data, laboratory experiments, and temperature and humidity monitoring (thermal sensors). Notably, this category comprises all forms of physical measurements and empirical research, yet it contains only eight studies. As shown in Figure 4, seven studies performed interviews or surveys to obtain data, grounded on/supported by literature, while twelve studies are solely based on literature reviews. The section titled "Others" consists of only two studies that did not fit into any of the other categories. One of them develops an adaptation pathway framework, while the other study presents a modular approach to resilient housing. The fact that most of the research conducted on climate adaptation is grounded in desktop studies is one of the main findings of this article.

3.2. Building Envelope

3.2.1. Greening

Several studies have investigated the impacts of greening on thermal comfort and energy consumption in buildings in the face of climate change. The concept greening is understood as green roofs and facades, as well as plants and trees in the outdoor environment. The influence of greening on thermal comfort and energy and water consumption in Paris, were evaluated by de Munck et al. [10]. Results show that during heat waves, the greening generated maximum cooling varying between 0.5 and 2 °C, and that green roofs help reducing energy consumption all year around. A similar study was done by Virk et al. [11], where the effectiveness of retrofitted green and cool roofs was simulated in a typical office in Central London. It was found through microclimatic modelling that green and cool roofs reduce near surface air temperatures, and in a 2050 climate scenario they both contribute to annual energy savings.

The qualities of the vegetation and substrate in green roofs, and the effects of watering, were examined by Maclvor et al. [12]. Using a replicated extensive green roof, it was discovered that non-irrigated Sedum provides an increased cooling effect compared to irrigated meadow mixes. Irrigated Sedum in 10–15 cm organic substrate had the overall best performance. For roof cooling, 2D compact plant covers were found to be more important than plant structures. Scharf and Zluwa [13] had a different approach investigating green roof influence. They tested the insulating performance of seven different green roof systems (differing in thickness, materials, and construction layers) over a 15-month period. A detailed description of the different types was provided, with the intention to help researches improve the accuracy of green roof simulations. Relevant factors were found to be: Construction thickness, water capacity of growing layer and drainage material, their pore volume, and utilization of drainage boards.

The contribution of green roofs for passive warming in tropical regions during winter was investigated by Jim et al. [14], as a climate change adaptation measure. It was found that green roofs work as a repository of solar heat. Thermal capacity increases with thicker and porous substrates, and warm green roofs create a thermal gradient to transmit heat downward to indoor space. Guzmán-Sánchez et al. [15] developed a methodology to assess the impact of different roofs on sustainability. The analysis was performed in Mediterranean, Oceanic and Continental conditions. Green roofs were shown to be the most resilient option under all climate scenarios. A literature review concerning thermal performance of green facades was carried out by Hunter et al. [16]. Most studies examined tended to research design problems, while there was a gap in studies treating the impact of plant morphology and physiology in façade performance.

Factors for implementing green roofs in Thailand were analyzed by Sangkakool et al. [17]. The potential of reducing the UHI-impact is looked upon as a main reason for adoption, while lack of skilled workforce and knowledge restrain the evolvement.

3.2.2. Material Selection

In light of the raising temperatures induced by climate change, Zinzi [18] investigated the potential of cool façade materials. An analysis was conducted to assess the influence of cool painting on the thermal response of an Italian residential building. Cooling energy consumption was reduced by 10–20%, and peak operative temperature was reduced in the range of 0.5 to 1.6 °C. Further, during the peak irradiation hours, the external surface temperatures were reduced by more than 6 °C. Perreault and Shur [19] focused on treating the issue on how to adopt buildings to climate change in permafrost regions. It was found through analysis that summer seasonal thermal insulation cools the soil and is significant for improving foundation integrity in a warming climate. Further, seasonal insulation will be of importance for adapting existing arctic buildings to the expected raising temperatures, and the amount may be selected based on future climatic predictions. On the contrary, utilization of permanent insulation will increase the permafrost temperature. The research by Lü et al. [20] was based on dynamic simulation modelling of wooden buildings' hygrothermal performances under climate change. It was found through assessment of the climatic suitability of wood and existing wooden buildings, that wood building materials constitute an effective response to climate change.

In light of the pressing issue of urban heat island effects and climate change, Yang et al. [21] have reviewed the use of reflective materials on buildings. It shows that the capability of reflective materials depends on different factors, that city planners need to take precautions, and that the strategy has to be developed on a city-to-city basis. Yumino et al. [22] did research concerning measures for mitigating and adapting to urban global warming. It was discovered that highly reflective materials had a negative impact in terms of adapting, and greening is not noteworthy effective. As the implications of climate change on thermal comfort and cooling loads are substantial in the UK, Sajjadian et al. [23] investigated how phase-change-materials (PCM) can mitigate this impact. Through dynamical thermal simulations, it was shown that adequate utilization of PCM, will cause a reduction in total discomfort hours and cooling energy loads.

3.2.3. Design Strategies

Andersson-Sköld et al. [24] aim to reduce the risk of maladaptation to climate change by implementing a systematic, integrated approach. Alternatives to reduce the risk of heat waves, flooding and air pollution in urban settings were evaluated. These include well-considered usage of trees and shrubs, compact building design with light colors and large green areas. Another study concerning adaptation to the predicted increases in flooding and overheating, is presented by Keeffe and McHugh [25]. They introduce the detailed concept of a modular house, IDEAhaus, which is flood-proof to a depth of 750 mm and utilize passive cooling techniques. Sajjadian [26], on the other hand, has taken the issue of increasing temperature into account while evaluating the choice of construction systems (lightweight or heavyweight) with varying thermal mass. Based on thermal comfort and energy consumption, the performance of different construction combinations is evaluated for current and future climatic impact in London, UK. Results show that heavyweight construction systems have a limited advantage in a changing climate.

A different approach for evaluating passive climate change adaptation measures was done by van Hooff et al. [27]. Building simulations were conducted on three typical residential buildings in the Netherlands to investigate the importance of increased resistance, changed thermal capacity, increased short-wave reflectivity (albedo), vegetation roofs, solar shading, and additional natural ventilation. Results indicate that the most effective factors for reducing the number of overheating hours during a year, are additional natural ventilation and exterior shading. A similar study was done by Jiang and O'Meara [28] in Florida. Cooling demands were simulated by utilizing projected weather data in the periods of 2020 to 2100. It was found that increasing the roof thermal resistance was less efficient than increasing the thermal resistance of the wall. Recommendations on values for window's visible transmittance and solar transmittance of glazing materials and its thermal resistance were also given.

The durability of a passive house wall assembly was investigated by Sehizadeh and Ge [29] under current and future (2020, 2050, 2080) climate scenarios in Montreal. While decay risk of plywood cladding is likely to decrease under future climate, the mold growth risk is expected to increase. The frost damage risk for bricks is found to not increase.

Analyses of the climatic change on different types of historic buildings in Oravita, Romania, is presented by Mosoarca et al. [30]. Since the more extreme climate accelerate the degradation and failure of heritage structures, understanding the future climatic impact is important. The study emphasizes the importance of developing new climate impact methodologies. Fiorito and Santamouris [31] present a litany of new technological solutions for climate change adaptation and mitigation, including urban greenery, cool materials, and retro-reflective materials. They accentuate that the architectural profession plays an important role to fight climate change.

3.3. Precipitation and Wind Impact

Research on how the climate change affect different weather factors, which involve rain, snow and wind loads, are gathered in this section. Nik et al. [32] simulate how climate change affects wind-driven rain on a traditional built wall in Gothenburg, Sweden. Results show that more moisture will accumulate in walls, but climate uncertainties can cause variations. Similar impact assessment for eight UK sites is given by Orr et al. [33]. It was found that shorter but more intense rainfalls, increased runoff and biological growths on buildings are to be expected with climate change.

An evaluation of wind speed and snow load in Canada is presented in Jeong and Sushama [34]. Through simulations based on Canadian Regional Climate Model, it was suggested that the future 50-year return levels of wind speed and air pressure will increase. The projected snow load in the southern part of Canada is decreasing, while in northerly regions it is expected to increase. Projections of snow load was also evaluated in Croce et al. [35], who presents a procedure for calculations of snow load on ground based on daily temperatures and precipitation. For the period 1981–2010, it was shown that the snow load is increasing, compared to the reference period.

Determination of the effects of climate change on metrological parameters and further the energy use in buildings is analyzed by Cao et al. [36]. Design outdoor temperature for five major climate zones in China was evaluated based on climate data from 1961–1990 and 1981–2010. The evaluation showed that climate change impact on design loads is more significant during winter than summer, which could have a positive effect for building energy-saving design.

3.4. Design Tools for Integrating Climate Projections

How to integrate climate projections into building simulation is an eminent issue, as is which tool to use when. Procedures assimilating climate projections and a breadth of climate information into building simulations, are considered in Jenkings et al. [37]. This study can be seen in relation with Nik [38], who also suggests a simplifying method for implementing climate change impact assessment in building simulations, using regional climate model (RCM) weather data. As a continuation on this research, Nik [39] synthesize two more groups of weather data sets for future climate, based on dry bulb temperature, equivalent temperature and precipitation. Wall simulations are assessed and compared to the original RCM weather data, which shows that the method decreases the number of simulations and that results still are accurate enough. A similar study is done by Zhu et al. [40], who propose an alternative to the Global Climate Model for regional-scale weather prediction. They present a model to predict future monthly temperatures in Shanghai. Building simulations show that this method gives a more accurate result while characterizing the temperature trends, hence it has a better performance for predicting future temperatures in Shanghai.

Dubois et al. [41], on the other hand, investigate if a design support tool (DST) concentrating on adapting cities to rising temperatures can improve knowledge and skills of architects and designers in the field. Through workshops and testing, "hybrid" tools were found to be most appropriate, but the results question the capacity of one single DST to meet the requirements.

3.5. Frameworks and Guidelines

Frameworks for how to design resilient, climate-adaptable buildings are discussed by Basyyouni [42], Voskamp and Van de Ven [43], and Keenan [44]. The framework in [42] includes economic, social, environmental, and obsolescence factors, as well as a list of possible climate adaptation measures.

An overview and analysis of the existing guidance material in Norway is presented by Hauge et al. [45]. Through analyses and interviews it is suggested that the tremendous amount of "user guides" can lead to confusion and uncertainty among users, and a large share of them do not impart the climate change adaptation at an adequately detailed level. This study can be seen in relation with Glaas et al. [46], who analyzes compliance between climate risks and guidelines in Scandinavia. A lack of guidelines concerning future climate impact risks is pointed out.

With the intention to support the development of a National building sustainability assessment method (BSAM) in Iran, Malek and Grierson [47] present a framework to give information to implement a regional-based tool for adaptation to climate change.

3.6. Overheating

Overheating due to rising outdoor temperatures as a result of climate change and the urban heat island effect is a major problem addressed in several studies. Most of the research has a focus on larger cities where this problem already is a fact. Hamdy et al. [48], whom investigated the climate change impact on overheating and possible solutions, found that overheating in dwellings is an essential cause of many problems, and it is expected to increase with time. In a study by Pathan et al. [49], where 122 London dwellings were monitored during the summers of 2009 and 2010 for overheating assessment, it was found that it is a significant problem under the current climate. It is worst in bedrooms and it can aggravate in the future. Another example from the UK, Patidar et al. [50] investigate the overheating risk and a building's vulnerability to extreme events. Using a statistical model, impacts of climate change on temperatures were illustrated over the overheating period (May–October), implementing over 3000 probable future climates. A similar study by Taylor et al. [51] examines the overheating risk in London dwellings under the present and warmer future climate, with the objective to evaluate whether the conclusions from location-specific studies can be applied to different cities. The indoor temperature differences were driven by building orientation and retrofits, and relative dwelling overheating risk was identified within climate regions.

Urban heat risk management has become essential, something Kingsborough et al. [52] have addressed, employing an adaptation pathway methodology. They use climate change projections to see the changes in urban-land cover and the urban heat island effect to evaluate adaptation pathways and long-term adaptation planning. It was shown that focusing only on current practices for urban greening or building level adaptation is not sufficient to cope with increasing risk levels. It is noted that air-conditioning may be used to counter overheating on a building-by-building basis, but its increased usage will exacerbate the urban heat island effect and increase the overall overheating risk in the area.

Makantasi and Mavrogianni [53] evaluate different retrofit measures to prevent overheating in London. Fixed shading reduced the overheating hours by 28%, while movable external louvers had even more positive impact. Internal applied wall insulation and low ventilation rates will possibly cause overheating, while natural ventilation can prevent overheating in some of the cases. Another study, also concerning insulation performance in the face of overheating, by Fosas et al. [54], shows that increased insulation in poorly-designed buildings can increase overheating. On the contrary, in well-designed buildings, increased insulation can have a reducing impact on overheating.

Current and new regulations to reducing energy consumption, especially in cold climates, could affect the overheating risks in dwellings, which Mulville and Stravoravdis [55] have investigated. Through building simulation, each building structure is considered based on how it thermally will perform under current and future climate change predictions. The study concludes that today's building practice to minimize energy use, combined with current ways of overheating risk assessment, could lead to substantial levels of overheating.

Liu et al. [56] present approaches for development of current and future weather files. Two probabilistic hot summer years were proposed, and there was noticed an important limitation in using different metrics to compare overheating years.

3.7. Thermal Comfort

Maintaining indoor thermal comfort during summer has become a major issue and will grow worse along with climate change. This is shown by Yildiz [57], who simulated the climate change impact on a typical apartment building in Istanbul. Another example, from São Paolo, Brazil, Alves et al. [58]

came to the same conclusions. Sailor [59] investigates the role of global and local warming on indoor thermal comfort in representative buildings in two warm climates in the U.S. It was found through building simulations that failure of air-conditioning will have major consequences for the indoor comfort; the maximum summer indoor temperature can increase by 10–14 °C.

Thermal comfort and overheating risk in educational buildings in Cyprus were investigated by Heracleous and Michael [60]. Through dynamic simulation, it was found that natural ventilation can cope with the current climate from a thermal comfort perspective, but not in the future. In the context of climate change, Barbosa et al. [61] perform a literature review focusing on vulnerability factors that affect thermal comfort in residential buildings. Results indicate that balancing mitigation and adaptation is important when selecting new building design and retrofitting of old buildings. Another study by the same authors [62] offer a vulnerability framework and methodology for thermal comfort assessment in existing dwellings. Variations on physical characteristics and occupancy of dwellings are examined, and results are compared based on analytical and adaptive models. It was noted that vulnerability could be significantly decreased by the implementation of optimal insulation and ventilation.

3.8. Health Impact

Various health risks of indoor environment related to climate change and possible adaptation effects in the UK, were investigated in by Vardoulakis et al. [63]. It was found that to a great extent, the effects of climate change do have an impact on public health, and that adaptation measures in homes can counteract these impacts. Improved building design and passive measures can reduce overheating risk, while reduction of internal loads and ventilation can improve indoor air quality. A similar study by Fisk [64], discusses how climate change affect indoor environment and attached potential health consequences, with a focus on residential buildings in the US and Europe. This can be seen in relation with Chang et al. [65], which concerns the climate change impact on indoor air quality in South Korea. An indoor air quality model (IIAQ-CC) was established to evaluate the influence of climate change on indoor pollution level. It was shown that under RCP8.5 projections, mean formaldehyde levels would increase up to 4 times.

Implications of urban heat island effect combined with climate change in the west midlands of the UK, and possible adaptation measures, are considered by Taylor et al. [66]. It was found that shutter installations and energy efficiency retrofit may reduce mortality by 52%. Another study concerning heat stress resilience is shown in Hatvani-Kovacs et al. [67], which intent to improve the populations resilience to heat stress in Adelaide, Australia. Here, the increased intensity of heatwaves is a forthcoming problem due to climate change, exacerbated by the urban heat island effect. Heat stress resistant buildings were proved to be beneficial, as well as air-conditioning to some extent.

These studies can be seen in relation with a study by Bundle et al. [68], which aims to make research on indoor overheating due to climate change more accessible to public health teams.

Further, San José et al. [69] used a dynamic tool to understand the impacts of global climate on citizens' health. Urban buildings and urban atmosphere in Chelsea and Kensington (London, UK), were considered while mapping the health impact depending on the city's geometry. This shows how the tool can highlight exposed areas to evolve a design strategy to mitigate the effects of climate change on people's health. Liu et al. [70], on the other hand, study the mortality in cities due to overheating based on characteristics of the buildings and the local environment. They propose a method to map the spatial variability in overheating and heat-related mortality, now and in the future. It was found that the differences in architecture and shading solutions are of more importance than the variations in climate.

Current research on building-related heat stress and numerous heat indices is reviewed by Holmes et al. [71]. The research is linked to the development of a new heat-safety metric for use in passively conditioned buildings. The study recommends using wet-bulb globe temperature (WBGT) and predicted heat strain (PHS) indices for modelling and monitoring of indoor heat stress in healthy adult populations.

3.9. Sustainability and Resilience

Conservation of existing buildings exposed to additional wear caused by climate change is discussed in Luciani and Del Curto [72]. It is explored whether the concept of resilience is consequential for the "framework of sustainable building conservation". Saha and Eckelman [73], on the other hand, has intended to map how projected climate change affects the concrete degradation in cities. Through geospatial analysis they were able to assess the vulnerability of specific buildings. They establish that the corrosion depth may increase over the next 60–75 years, and that in a coastal climate, chlorination-induced corrosion is a bigger problem than carbonation. Another approach to increase the resilience to climate change is to find robust cost-optimal energy retrofit solutions for existing buildings, which is investigated by Ascione et al. [74]. In Rubio-Bellido et al. [75], the new Chilean standards for sustainable social housing are analyzed to investigate the indoor comfort in the context of climate change. The research determines that it is currently possible to reach improved indoor conditions 99.67% of the time without using mechanical systems, but this will decrease to 88.89% of the time in the future.

3.10. Policy

Physical climate adaptation strategies are discussed by Roders and Straub [76]. The possibility of adopting five implementation strategies were assessed by decision-makers in Dutch housing through an online survey. Risks on building assets in the UK associated with climate changes are reported in Boussabaine et al. [77]. Building stock owners and professionals in the UK were surveyed, and the findings were analyzed to improve their understanding of climate change risks and the impacts on their assets. Furthermore, Hurlimann et al. [78] investigate barriers to climate change adaptation. Buildings contribute to greenhouse gas emissions and are vulnerable to climate change, which makes development in this field significant. Twenty-one key Australian stakeholders were qualitatively interviewed to find adaptation barriers and recommendations. Regulations, language, unaffordability, and lack of awareness and demand was mentioned as adaptative barriers, while their recommendations include regulatory form and that relationship with other sectors should be considered.

4. Discussion

In this paper, we set out to address what is known from existing literature about climate adaptation measures for buildings, and what are the most important gaps in the research. Using the methods discussed in Section 2, it has been possible to eclipse the vast majority of relevant scientific material published in the field over the past five years. The results obtained are therefore believed to be as comprehensive as possible within the investigated time period and the contents of the databases. As such, it is equally important to review the extent of the literature as its content. Any gaps discovered in the material are of particular interest, as they highlight what research is missing in this important field.

There is a notably small body of literature on climate impacts on and adaptation measures for buildings. As this scoping review indicates, the literature covers a wide array of topics, but trends can be observed in the available material. Thirty-seven of the studies (a bit more than half of the identified literature) take future climate scenarios into account, usually through computer simulations. However, the investigated future scenario simulations tend to focus on temperatures, and only three studies are considering the implications of increased rain or wind loads.

The most central climate change impact mentioned in the studies is the prospect of rising temperatures, causing drought and heat stress. Increasing rain loads and intensities are also pointed out as forthcoming and large problem, especially in places where this leads to more storm surges and flooding. However, although this is a major problem, few articles treating this issue were found. In general, little research has been found on the effect of future rain events on buildings. It is well known that the global snow load will decrease in the future, but research in this study shows that it will in case increase some places. Even though it was found some studies on the impact of climate change on buildings in cold countries (including Sweden, the UK, and Canada), there is a clear deficiency of literature from cold regions in general.

There is also a major lack of studies where future climatic conditions have been used as a basis for laboratory experiments or field measurements, only three were found. The majority of the identified studies had their basis in computer simulations, theoretical models, or literature reviews. This suggests that research into climate adaptation rarely uses a "hands on" approach where predicted scenarios are tested in practice.

Furthermore, the bulk of the adaptation measures discussed in this research include greening, cool materials, and phase-change materials. All these measures deal with hotter weather. There are notably fewer articles based on measures for adaptation to wetter weather. Some of the identified studies have tried to make design tools to better estimate the future weather and its impact on buildings, but the climate modeling is still too little specific to be useful on a building scale.

5. Conclusions

This scoping literature review constituted a second step by the authors toward exploring what is known about climate implication and adaptation measures for buildings. Relatively little literature is found, considering the scale of the field and the importance of climate adaptation for the building industry. The identified literature touches into several different themes, with the bulk of the material focusing on problems related to increasing temperatures. However, there is a certain lack of material concerning the implication of climate change and relevant adaptation measures in cold climates. Little concrete has been found on the effect of future rain or wind events. Moreover, there is an inadequate amount of studies based on physical experiments.

It seems obvious from the results obtained in this study that extensive research based on physical measurements in the laboratory or in the field is needed to further understand the need for climate adaptation. From a Norwegian perspective, studies based on moisture, either in the form of precipitation or as building moisture control, will be of particular interest.

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Paper 2

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Review

Performance of Blue-Green Roofs in Cold Climates: A Scoping Review

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Abstract: Green and blue-green roofs are emerging as an increasingly popular feature of rooftops, particularly in urban areas. Particular problematic conditions render their usage complex in the Nordic countries. In order to ensure that green roofs are built durable and with the service life expected of them, it is important to know all the relevant factors surrounding their construction and operation. A scoping study was conducted in order to gain an overview on green roof research and available scientific literature. One hundred articles of particular interest for Nordic climates were retrieved and their findings summarized. It is found that the vast majority of green roof research has been conducted on a theoretical basis, or with practical measurements on green roof test beds or isolated components. There is scarcely any literature on the operation of full-scale, building-implemented green roofs, and no articles were found on the building technical performance of aged green roofs. These knowledge gaps indicate a major risk factor in green roof operation, as their performance and integrity over time has not been documented. This despite the fact that green roofs have been implemented and in operation worldwide for decades.

Keywords: blue-green roof; green roof; cold climate; multi-disciplinary performance; state-of-the-art; scoping study

1. Introduction

In the Nordic countries, climate change is expected to manifest in the form of warmer, wetter weather. It is already estimated [1] that average annual rainfall in Norway has increased by 20% in the past 100 years. The frequency and intensity of large rainfall events have also increased, and are expected to increase further throughout the 21st century. At the same time, urban densification has continued; with larger fractions of ground surfaces being paved over and impervious to rain water, preventing local infiltration and leaving more stormwater on the surface. The combination of these factors means that traditional urban stormwater management solutions and strategies are no longer sufficient.

In a response to this dilemma, local retention of stormwater has emerged as a popular climate adaptation measure. An aesthetically pleasing solution involves living plants in rain beds, which also allows for local water infiltration and evaporation. Such so-called "blue-green solutions" may also be incorporated on building rooftops, in the form of slightly modified green roofs. Utilization of roof space is gaining interest, as land is a premium in urban areas. Hence, green roofs are becoming an increasingly popular feature in urban contexts.

However, integration of such a new element in buildings requires careful consideration of building physics (transport of heat, humidity, and air in building constructions). Water of any form, except in plumbing, is generally undesired inside a building envelope, and a blue-green roof solution involves permanently mounting a biologically active and occasionally water-saturated slab in immediate contact with the building's outer envelope. Planners will have to be careful and considerate to ensure that none of that water ever finds a way into the building construction for the duration of the roof's service life.

Green and blue-green roofs have been built in a variety of climate zones. Thodesen et al. [2] review many of the challenges relevant to green roof operation in Nordic countries. In cold coastal climates, highly specific challenges arise. These include temperatures that fluctuate greatly over relatively short time periods, widely varying amounts of precipitation, and daily freeze-thaw cycles. Additionally, even small geographic areas can contain widely different climate zones. In Norway, many cities are built in steep hillsides along the coast, with great altitude differences over short distances and temperatures that vary accordingly. Precipitation may fall as rain at sea level, while building up thick layers of snow just a kilometre away.

Trends and demand [3,4] suggest that blue-green roofs will become the norm for commercial flat roof constructions in the coming years. However, building blue-green roofs under Nordic climates requires cross-disciplinary knowledge about their behaviour and response to various circumstances. In order to examine this general inquiry, the following research questions are addressed:

1. What are the main areas of research concerning green roofs in temperate to cold climates?
2. What are the main challenges investigated?
3. What are the main knowledge gaps?

This article is written as part of the Norwegian research initiative Klima 2050 (www.klima2050.no), a cooperation between research institutions and the industry concerning climate adaptation of buildings. As green roofs are considered an important climate adaptation measure, knowledge about their implementation and operation is sought, particularly in a risk assessment perspective. The scope of the research presented in this article is thus limited to map the risk factors of blue-green roofs from a building technical perspective, and seek mitigation measures in policymaking. For this, a thorough understanding of blue-green roof construction and operation is required, as well as relevant physics. In this review, international research literature is studied to map the current knowledge about blue-green roofs relevant to Nordic climates, and to identify knowledge gaps, with the main focus on extensive and semi-intensive green roofs (see Section 2.3 for definition). The perspective of this research is on categories C (maritime temperate climate) and D (continental climate) of the well-known Köppen-Geiger classification system. These classifications extend down to Central Europe, where the cooling aspect of green roofs is a central issue. However, cooling is not a topic of focus in this article because of the high degrees of roof insulation in Nordic countries.

2. Theoretical Framework

2.1. Blue-Green Roofs

Blue-green roofs are roofs wherein vegetation and elements of stormwater management are combined in the roof structure. In theory, this makes green roofs a subset of blue-green roofs, but in practice the terms are synonymous, as long as the green roof is actively utilized for stormwater management. According to Shafique et al. [5], a "green-blue" roof is a green roof with an extra water storage layer, beyond what is required for the plants to survive. Another definition suggests that any green roof becomes a blue-green roof if it is built explicitly as part of a stormwater management system. The definitions correlate, as one would not build bigger water storage than necessary without having a secondary function in mind. This article will consider the entire blue-green roof assembly, from the plants down to the interior ceiling, and not only the layers above the roofing membrane. This consideration is not necessarily shared by all examined literature, as several of the articles only regard parts of the assembly.

2.2. Stormwater Management

Green roofs are increasingly commonly used to manage stormwater through water retention, runoff delay, and runoff reduction through evapotranspiration. A portion of the stormwater is retained in the green roof assembly, and gradually released to reduce the peak runoff rates into the downstream drainage system or recipient. Green roofs are classified as one of many solutions for local stormwater management. They are considered more aesthetically pleasing than traditional "grey" solutions [6], and more suitable for building retrofits since they do not require extensive ground works and mass transport.

2.3. Green Roofs in Cold Coastal Climates: The Case of Norway

Vegetated roofs have been built in Scandinavia since ancient times [7], but those traditional (often entirely turf-based) solutions bear little resemblance to modern green roofs. Green roofs built over a roof membrane were popularized in Berlin in the early 20th century [8], a design that has been modernized in the decades since. Green roofs are commonly divided into two categories, extensive and intensive green roofs. Their definitions are far from exact [9,10], but it is generally agreed that extensive green roofs consist of a thin mat of vegetation with a substrate layer up to 100 mm thick. Intensive green roofs feature significantly thicker substrate levels, larger plants, and may even resemble parks with trees and water features. A third category, semi-intensive green roofs, is sometimes applied to bridge the two.

Green roofs in Norway are typically applied on flat roofs, either one floor above street level to provide an open, green space between the upper floors of urban buildings, or as extensive roofs with primarily aesthetic purposes. Regardless of application, green roofs tend to be built using a conventional, low sloped, compact roof as a foundation [11]. Norwegian building regulations decree a minimum roof slope of 1:40 [12]. Due to icing problems, conventional low-slope roofs tend to utilize internal drains, with overflow drains through the roof parapet. The regulations also demand buildings to be highly insulated, with roof U-values of 0.13 W/(m^2K) or lower, as well as similar levels of wall and ground insulation. The Norwegian Standard NS 3840:2015 [13] governs extensive green roofs, and a standard for intensive green roofs is currently under development.

2.4. Challenges of Blue-Green Roofs

One of the main challenges to blue-green roof operation is the threat of water leakage through the roof membrane. Water in the building envelope may lead to deterioration of insulation materials, corrosion, electrical failures, or facilitate biological growth. It is of vital importance that the roof membrane stays waterproof, particularly since it is practically impossible to detect leaks as the roof membrane is buried in a very literal sense of the word.

Stormwater management is the primary purpose of a blue-green roof. Functionality throughout its entire service life, without excessive maintenance including the drains and the lower, hidden layers of the roof assembly, is vital. Beneficial growth conditions for plants is another issue. The conditions on the roof need to be livable long term; otherwise, the roof will not remain green.

3. Method

3.1. Scoping Study

The literature review was carried out in the form of a scoping study, as described by Mays et al. [14]. Scoping studies, as described by them, "aim to map rapidly the key concepts underpinning a research area and the main sources and types of evidence available, and can be undertaken as stand-alone projects in their own right, especially where an area is complex or has not been reviewed comprehensively before" (2001:194). This study has been carried out largely following the six-stage framework suggested by Arksey and O'Malley [15]: (1) identifying the research question; (2) searching for relevant studies; (3) selecting studies; (4) charting the data; (5) collating, summarizing and reporting the results; and (6) consulting with stakeholders to inform or validate study findings.

Levac et al. [16] state: “scoping studies are ideal because researchers can incorporate a range of study designs in both published and grey literature” and “address questions beyond those related to intervention effectiveness” (ibid).

The initial research reported on in this article was carried out during the period of September–October 2017. Five scientific databases (Google Scholar, Oria—Norwegian library database, WebOfScience, Scopus, and ScienceDirect) were examined for relevant papers, with a total of 180 individual searches.

3.2. Search Terms

Green roofs comprise the bulk of blue green roofing solutions available, naturally receiving a large focus in this study. The majority of search terms followed the format “’Green roof’ AND ____”. Search terms of this format included the term “Green roof” paired this way with the keywords listed in Figure 1.

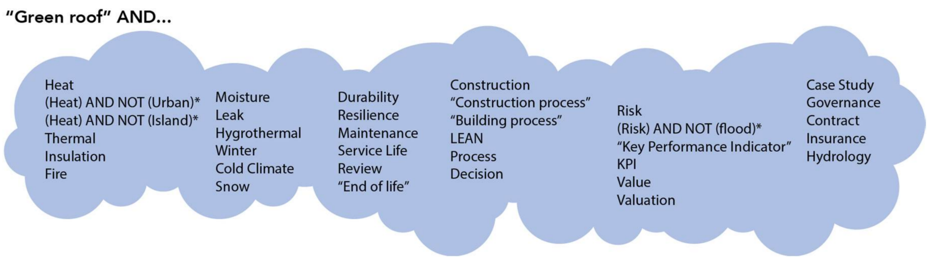

Figure 1. Keywords and -phrases used in literature search, on the form “’Green roof’ AND ____”. Phrases marked with an asterisk (*) were modified according to the syntax of the different search engines utilized. Quotation marks were used for all search phrases, to ensure that the hits contained the exact wording of the phrase.

In addition, the following search terms and variations thereof were used:

- “Green roof”
- “Blue Green roof”
- “Green Blue roof”
- “Blue gray roof”/“Blue grey roof”

The number of hits concerning blue-green/green-blue roofs measured in the single digits for most search engines. Searches for blue grey roofs returned no relevant results, although this is understandable given that the term is very new and seldom used (a blue-grey roof being a paved roof that functions like a blue-green roof, but without the use of plants [17]). With more generic search terms for regular green roofs, tens of thousands of hits were returned from the largest databases, down to a few hundred for the smaller ones. More specific searches returned between zero and 1000 hits, depending on the size of the database. In order to produce a manageable list the most numerous result pools were filtered by searching again with more specific keywords, and sorting the hits by journals to do more thorough searches of journals considered particularly relevant. See Figure 2 for an example search narrowing conducted this way. Some papers were also found through citation chaining through the search engines. This method was used to discover a handful of papers, some with a high number of citations or degree of relevance, which had not shown up in search results.

3.3. Selecting Articles for Further Study

The study was limited to English-language scientific papers and scientific reports. Papers in peer-reviewed academic journals were greatly preferred, only certain exceptions were made for conference papers. By the criteria above, the study was also excluding web articles, books, and (in the case of Google Scholar) patents.

Articles regarding full-scale green roofs, preferably established before—and ideally, unrelated to—the onset of the research described in the article, were favoured. Realistic, full-time operational green roofs are subject to different design requirements, maintenance schedules, and budget constraints than samples in a test bed created to be operational only for the duration of the research, and the stakes surrounding their operation are higher. However, this factor served more as an inclusion criterion than one of exclusion; no articles were excluded due to a lack of a described green roof assembly.

The initial search results show up in list form, ranked by relevance as defined by the search engine. For searches with a low number of hits (roughly 150 or fewer), the entire list of search results was examined. Articles considered relevant from their title and/or abstract were included in the study. For searches with a greater number of hits, the first 100 articles as ranked by relevance by the search engine were examined. If more than 150 relevant articles were found, more specific searches were conducted including additional keywords (or excluded, for instance removing "flood risk" from a "risk" search). See Figure 2.

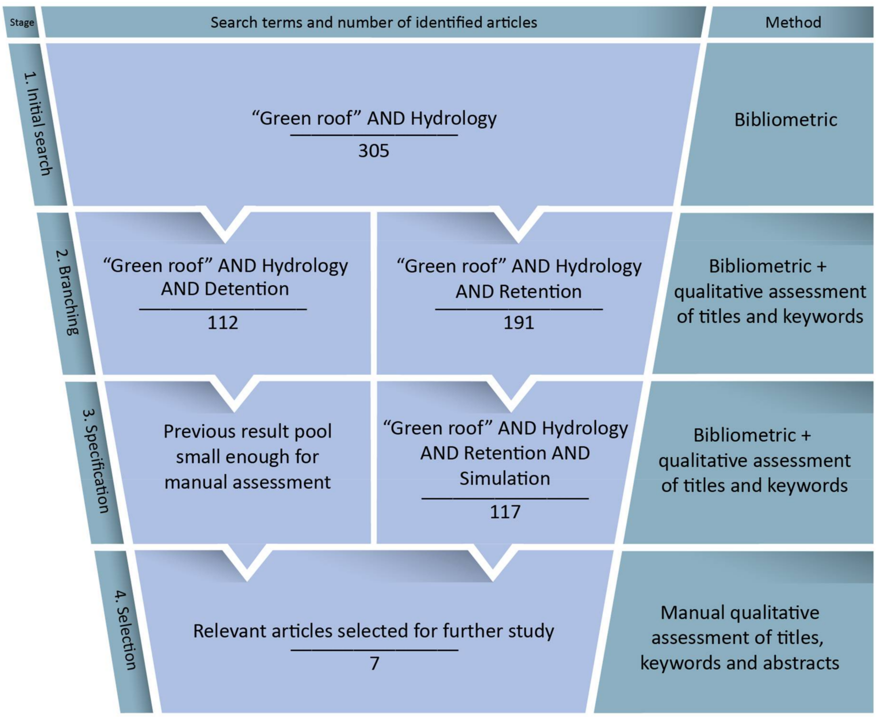

Figure 2. Example search procedure, narrowing a large number of search results into a manageable number for manual assessment.

As the study concerns the building technical aspects of green roofs, certain categories and results were excluded from the search. These include biodiversity, plant biology, and the Urban Heat Island effect, though some examined articles give some secondary attention to these matters.

A trait of scoping studies that might be considered a disadvantage, is that authors do not typically assess the quality of included studies, as commented by Levac et al. [16]. It is typically difficult to determine whether an article is useful for the study without reading it, which essentially means including it in the study anyway. A vetting round may therefore be applied between the initial search and the detailed analysis, to remove articles that turned out not to be relevant upon closer inspection, as illustrated in He et al. [18]. In this study, this resulted in the removal of five papers.

After an initial list of articles was compiled, selected professionals were asked to suggest any missing key papers from their fields of expertise, which added a handful of articles on topics of thermal insulation properties and hydrology.

3.4. Sorting of Articles

The studied articles were listed in a spreadsheet, with their attributes noted in columns for easy comparison. The articles were sorted into topic categories (Table 1).

Table 1. Topic categories.

LCA/Ecology	Pollution (Air/Water Pollution)
Energy (Building energy balance)	Aesthetics
Hydrology	LCC/Economics
Policy	Management, Operations and Maintenance (MOM)
Regulations/standards	Process (acquisition/planning process)
Thermal insulation (heat flow through assembly)	Others (i.e., acoustics, fire, history, etc.)

Between categories with some overlap and fuzzy borders it was attempted to establish functional categories. Ex. Policy/regulations. Noted attributes of the articles included publication year, country/institution of origin, keywords, and, if applicable, the specifics of any roof assemblies mentioned in the article. Review articles were counted, though not given a separate category, since they often contributed greatly to separate categories. Further, it must be noted that the categories are not to be considered discreet. For instance, the categories Energy, and Insulation overlap one another to some extent, and energy simulations might also be the basis for articles in the Economy or LCA categories.

3.5. Roof Assemblies

A large variation in green roof assemblies was found in the studied literature. Many assemblies were small roof plots created for research purposes, others were full-fledged green roofs designed for the building and meant to serve for decades. As the purpose of a green roof has great influence on its design process, it was decided to categorize the articles according to type of assembly. Each article was categorized by "degree of construction industry realism". It was decided to use the term "maturity" to describe this categorization. The maturity categories are defined in Table 2.

Table 2. Categorization of roof maturity categories in researched literature.

Maturity Category	Definition
0	The article does not consider a specific roof assembly
1	Computer simulation of specific green roof assembly
2	Tests conducted on green roof plants/components, but not in a roof assembly
3	Free-standing test plot, not mounted on building roof
4	Test plot on building roof, frames or buckets separate from existing roof assembly
5	Test plot on building roof, green roof constructed for research purposes
6	Green roof on building, built for research purposes but meant to serve beyond duration of research
7	Green roof on building, not built primarily for research purposes, newly built
8	Green roof on building, not built primarily for research, age >2 years at start of research
9	Green roof on building, examined at the end of a regular service life

4. Results

4.1. General Overview of the Material

The material spanned a wide range of topics, approaching green roofs from a variety of angles. Articles related to green roofs' energy performance, hydrology, and economical performance made up the bulk of the identified literature. The vast majority of articles concerned the operational phase of green roofs, with only some related to the planning, design, construction, or end-of-life stages.

While researched literature originates from all over the world, and their research may be geared towards specific situations in their respective countries, the findings can still be useful in a Nordic perspective. Hence, it is attempted to examine the literature globally and interpret their findings in a cold-climate context. A spreadsheet overview of the examined literature is available as a Supplementary File to the web version of this article.

4.1.1. Maturity

As shown in Figure 3, the majority of examined literature did not consider any specific roof assembles at all. These papers include most reviews, most articles on economy, and all articles on policies and regulations. Note that no identified articles fell under maturity category 9 (green roofs examined at or near the end of their service life), and there is a deficiency of articles describing "mature" roofs in general. The authors consider this one of the largest knowledge gaps uncovered in this study.

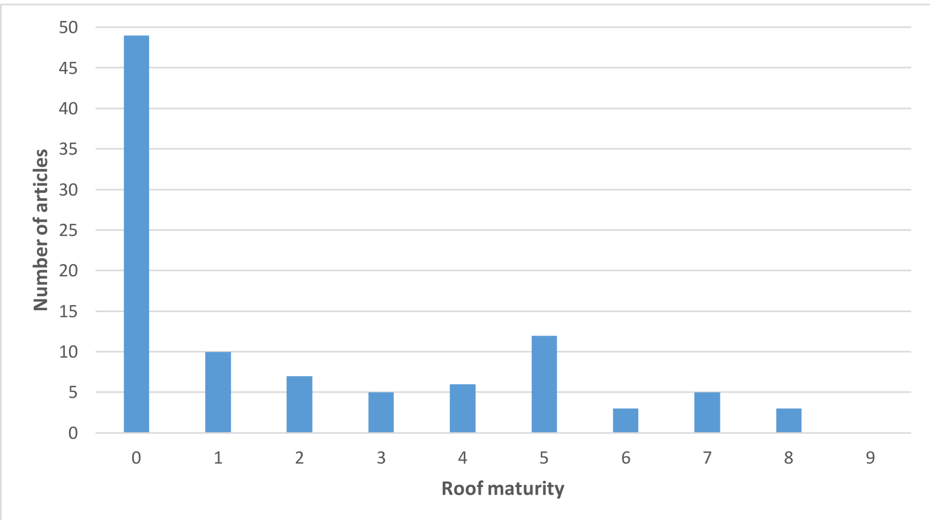

Figure 3. Number of articles by "maturity" of the roof assembly. The majority of investigated articles did not consider a specific roof assembly, hence the dominance of category 0. For a legend of the maturity categories, see Table 2.

4.1.2. Topic Categories

Each of the defined topic categories were represented in the research material, although some more often than others. There was a multitude of articles concerning the research of heat flows through green roofs, causing this category to be split into three focus areas; the heat flow itself; evaporative cooling; and the building's overall energy balance. Some articles in the Economy category included energy simulations, mostly for the purpose of calculating energy cost savings. Topical distribution overlaid with maturity is shown in Figure 4.

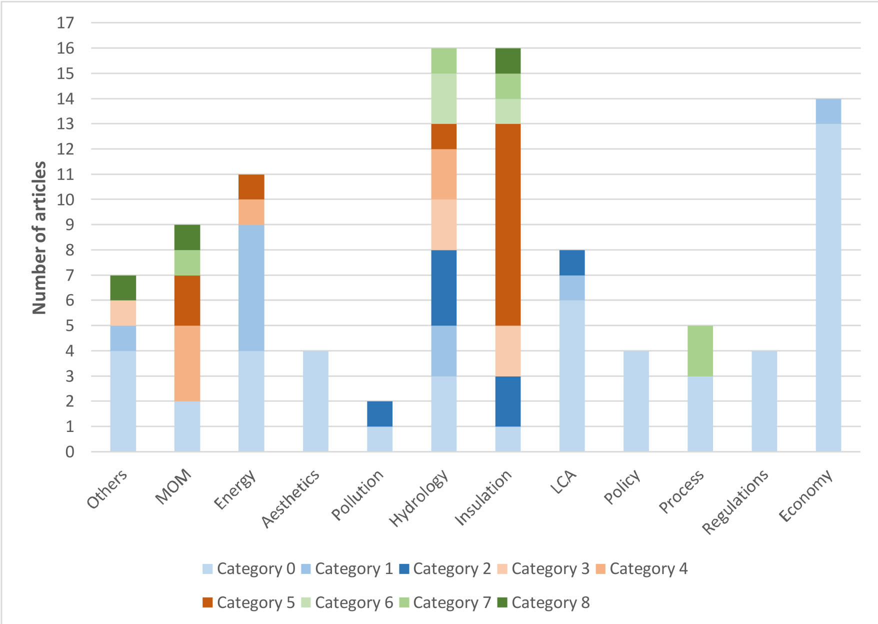

Figure 4. Roof maturity by article category. For a legend of the maturity categories, see Table 2. The colours roughly correspond to: Blue—no physical roof assembly; Red—test roof assembly; Green—roof not built for research purposes.

4.1.3. Articles by Year

All of the identified research articles were published after the year 2000, Figure 5, with an almost exponential growth the last decade. Note that this could also be due to a possible bias towards newer articles in the algorithms of the utilized search engines.

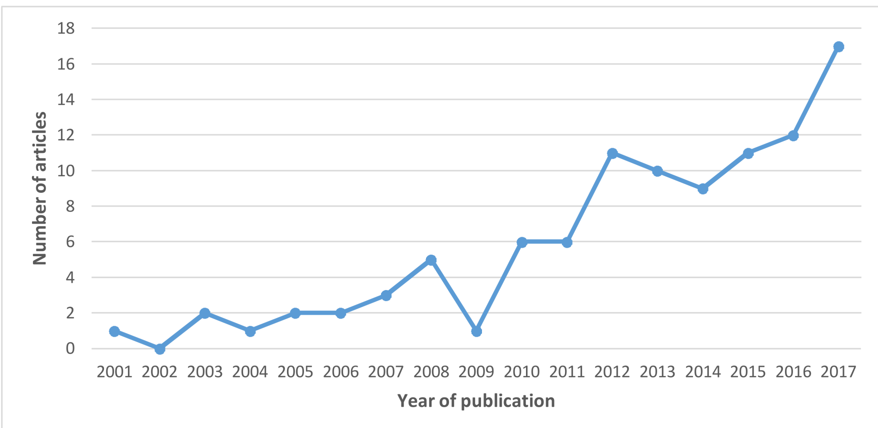

Figure 5. Number of articles found in the literature search by publishing year, up to 2017. No explanation has been found for the low number of articles from 2009.

4.2. Earlier Reviews

Among the 100 identified articles, 15 were review articles. The LCA category has 8% of the articles but 40% of the review articles.

4.3. LCA/Ecology

Within the material examined, the most prominent themes include overall qualitative benefits of green roofs, comparison between roof technologies, and quantification of environmental impact (components or whole roofs).

The knowledge regarding the qualitative ecological benefits of green roofs have previously been summarized in several review papers. Getter and Rowe [19] and Oberndorfer et al. [20] review the evidence for the benefits of green roofs and examine the biotic and abiotic components that contribute to overall ecosystem services. Both reviews document advantageous properties related to topics like air quality, stormwater management, habitat restoration, and improved roof membrane longevity. Future research directions are suggested, many of which have been addressed by articles found in this paper.

Berardi et al. [21] provide another review, with particular emphasis on water management and reduction of air pollution. Li and Yeung [22] give an overview of the environmental benefits of green roofs, as well as the barriers for applying extensive green roof systems. Non-native plant species were found to have a higher survival rate than natives in reviewed field tests.

Others have focused on comparing green roofs to other technologies that compete for roof space. In particular, Cubi et al. [23] compare the relative ecological merits/benefits of photovoltaic roofs, green roofs, and white roofs. Rooftop PV proved to be the highest-performing technology, while green roofs also have positive impacts. In a cold climate, white roofs are not found to have any net benefits. Vaček et al. [24] compared four different semi-intensive green roof assemblies in an LCA perspective, bringing up the question of substituting some of the growth medium with extra insulation material (mineral wool or EPS). This led to higher environmental impacts from production, but decreased it in later life stages.

The ecological performance of green roofs has also been modelled, in an attempt to quantify their ecological impact. Life cycle analyses are interesting in particular, but the subject has only been treated in one identified article. Bianchini and Hewage [25] describe an inventory analysis of green roofs, and life cycle analyses for the most common materials. Their findings connect the biggest impact to polyethylene materials utilized in the lower layers of green roofs. The other identified article on the subject, Tundrea et al. [26], considered a case study of a completely earth-sheltered house. It was found to have a lower environmental impact and thermal transmittance than a comparable building above ground. From the perspective of the authors, the qualitative aspects of life cycle analyses appear to be well covered in literature. However, although there is an overall agreement that the environmental impact of green roofs is generally positive compared to conventional roofs, few of the identified articles focus on quantifying the impacts and benefits. The question also remains on to what degree the addition of a green roof will impact the life cycle of the rest of the building. As green roof components above the membrane tend to be conceptually similar regardless of climate, the general findings in this category are considered to transfer well to a cold-climate situation.

4.4. Energy

The most prominent themes in this category include energy balance of a whole building, modelling or measuring energy flows, and reviews of different factors' influence on energy performance. Additionally, some articles regarding cooling of buildings through evaporation of water from the green roof were included in this category. The articles reviewing the energy balance of buildings equipped with green roofs tend to be based on computer models and simulations. Note that this category has significant overlap with the Insulation category, where articles were sorted if they focused more on quantifying the thermal flows through specific green roof assemblies. Some energy models are also presented in articles in the Economy category, if their primary focus is on energy cost savings in specific markets.

Castleton et al. [27] examine the potential energy savings of installing green roofs in the UK through comparing U-values, thermal mass and solar reflectivity. It is found that thicker layers of lighter, drier substrate will contribute more to insulation. Green roofs on well-insulated buildings will save very little energy, if any. Jaffal et al. [28] also studied the impact of green roofs on building energy performance, presenting a model and integrating it in a building thermal program. A moderate reduction in annual energy demand is found, mostly related to lower cooling demands in summer, and thus the savings are higher in warmer climates.

Sailor [29] describes a model to be implemented in EnergyPlus, simulating the energy and moisture balance of green roofs. Bass [30] lists and discusses factors in which the green roofs/walls affect a building's energy use in Toronto, Canada. The cooling potential in summer is stated to be the greatest factor reducing energy use, a conclusion in line with the above articles. Ascione et al. [31] verify the utility of green roofs, under environmental and energy points of view, by considering all the aspects that influence their performance. A simulated building is evaluated with several different roofing options in six cities in Europe. In dry regions, the irrigation cost can nullify savings in energy for air-conditioning. In cold regions, green roofs are more advantageous than "cool roofs".

Saadatian et al. [32] reviewed a set of nine energy-related aspects of green roofs including plant types, seasonal performance, cooling load, and heat flux. Findings confirm the general notion that the biggest advantage lies in reduced cooling loads, but other environmental benefits are recorded as well. Of particular interest is the reduction in roof membrane temperature. This is also recorded in Rakotondramiarana et al. [33], who compared green and conventional roofs under the climate conditions of Antananarivo, Madagascar. Even in warm climates, the impact of green roofs on indoor air temperature and energy demand is found to be almost insignificant for insulated buildings. In Barozzi et al. [34], an experimental monitoring campaign with focus on surface temperatures concludes that a green roof may reduce the external surface temperature by 10–20 °C for $I > 500$ W, and 0–5 °C for $I < 500$ W. During the winter season, the thermal gradients through the green roof are close to zero, owning to a well-insulated underlying structure.

Overheating of buildings is rarely an issue in the Nordic countries, and green roofs are unlikely to be built for the specific purpose of cooling a building. However, an evaporative cooling effect will be present regardless of whether one seeks to exploit it. It is important to know to what degree green roofs will cool a building, and if the effect should be compensated for or not. Moody and Sailor [35] found that evaporative cooling in spring and autumn may cancel out energy savings the rest of the year in certain climates (Portland, OR given as example).

In Pastore et al. [36], a case study describes buildings in Palermo, Italy, and the potential impacts on thermal comfort through various retrofit measures involving green roofs and walls. Building energy simulations show a reduction of average indoor temperature ranging from 0.2 to 2.5 °C, depending on the roof assembly and outdoor temperature. Solcerova et al. [37] investigated whether green roofs will cool the air surrounding the building. While the underlying building is cooled in daytime, the increased albedo of the green roof compared to a black roof is actually found to heat up the air. At night, evaporation cools the air, if water is available for evaporation.

The articles in this category conclude that green roofs contribute little to energy savings in well-insulated buildings during the cold season. In addition, it is shown that available literature puts a great focus on cooling properties. Even these properties are reduced greatly on well-insulated roofs. This suggests that the energy benefit of green roofs in the Nordics would be negligible at best, and that the roofs should primarily be built for other reasons.

4.5. Hydrology

Green roofs are interesting from a hydrology point of view for their water holding capacity, and subsequent consumption of water through evapotranspiration leading to temporary detention of runoff and permanent retention through evapotranspiration. Key themes in the material include monitoring of stormwater runoff reduction (retention), water storage capacity (detention), and growth medium analyses.

Retention performance—that is, the amount of stormwater that will not become runoff the roof—is perhaps the most studied hydrological property of green roofs. It has been investigated through numerous field studies. In Bengtsson et al. [38] the hydrological function of a thin, extensive green roof in Sweden is investigated. It is concluded that even a thin green roof (40 mm) can reduce the annual runoff by approximately half. In Villarreal and Bengtsson [39], several controlled runoff experiments are performed on a Sedum green-roof. Results indicate that roof slope had no effect on the direct runoff hydrograph. The retention capacity was affected by whether roofs were dry or wet, with dry roofs having more retention capacity available. Carter and Rasmussen [40] investigated the potential for stormwater control using green roofs. The roof's capability to delay peak runoff and retain flows were measured. In Stovin et al. [41], the hydrological performance of a green roof test bed was monitored over a period spanning a little more than two years. The annual performance figures are in the lower end of a range of international data, probably because of climate conditions (in the UK) that are colder and wetter than average. A model predicting runoff was attempted, but found to be insufficient due to the complexity of inter-event processes. In Fassman-Beck et al. [42], four extensive green roofs in New Zealand are evaluated over extended periods for stormwater retention. Up to 56% cumulative retention was measured, with runoff rarely occurring from storms with less than 25 mm of precipitation. Seasonal retention performance decreased only slightly in winter. Stovin et al. [43] outline the development of a conceptual hydrological flux model for the long-term continuous simulation of runoff and drought risk for green roof systems. Sims et al. [44] measured the retention performance of green roofs in three different climate regions: Ontario (humid continental), Calgary (semi-arid, continental), and Nova Scotia (humid maritime). Drier climates were found to have greater cumulative stormwater retention by percentage. The impact of climate was greatest for medium sized storms. Antecedent moisture conditions (AMC) is proven a relevant indicator of retention performance in any climate. Johannessen et al. [45] calculated the potential retention, and subsequent optimal substrate thickness based on precipitation, temperature and potential evapotranspiration (PET) of green roofs in coastal and wet regions around the North Sea. Large differences in potential annual stormwater retention were found between locations, driven by differences in PET and precipitation amounts. Viola et al. [46] explore retention performance of green roofs as a function of their depth in different climate regimes. Intensive and extensive roofs are investigated.

Retention capacity has also been reviewed in two papers. Berndtsson [10] provides a review article discussing and comparing the different studies on hydrologic properties of green roofs. The effects on water pollution are also discussed. The relative large number of observed retention studies is summed up in a review by Li and Babcock [47], showing that green roofs can reduce stormwater runoff volume by 30 to 86%, reduce peak flow rate by 22 to 93%, and delay the peak flow by 0 to 30 min. Johannessen et al. [45] and Viola et al. [46] theoretically calculated retention performance which overall aligns with the set of observed studies measuring retention. This results in the possibility of design calculations-based hydrological performance. Showing that PET and precipitation patterns are the most important performance factors for green roof performance.

Detention—the delay of stormwater runoff—was not found to have been investigated as broadly in literature. Shafique et al. [5] discuss the potential of green-blue roofs to detain stormwater runoff. A test roof was established on a rooftop in Seoul. A single, very heavy rain event was analysed. The green-blue roof showed good detention performance.

Other authors have focused on how individual green roof components affect hydrological properties. Nagase and Dunnett [48] examine the water-runoff-affecting properties of 12 different species from three plant groups. In this study, species variety within a roof did not affect the retention capacity of the test area compared to monocultures. In general, grasses performed better than forbs or sedum. In Hill et al. [49], soil from 33 green roofs in the Southern Ontario region were sampled and analysed in a lab. In De-Ville et al. [50], the physical properties of 12 green roof substrate cores (some virgin, some 5 years old from green roof test beds) are evaluated using XMT imaging. There are significant structural differences (density, pore- and particle sizes) between virgin and aged samples, but they are not found to affect hydrological characteristics significantly. The precipitation pattern and flow path to the roof drain will be more important than substrate and vegetation characteristics for thin roofs. For thicker roofs the lateral flow through the substrate can give significant detention, described as unsaturated zone flow.

Overall, green roofs seem to be well suited for stormwater management. In general beneficial properties are well documented, in particular the capacity to retain water, even for thin substrate layers. The properties of the substrate and flow path are shown to have influence on overall hydrological performance. However, the examined literature does not mention how runoff from the roof is handled downstream. Once water has drained through the green roof (and possibly been measured), it appears to be ignored in hydrology literature.

4.6. Policy

These articles discuss various desirability policies or incentives regarding green roofs pertaining to specific cities or countries, as well as various practical issues to be addressed while implementing green roofs at a large scale.

Carter and Fowler [51] describe various requirements and incentives to encourage the use of green roofs in select US cities. Lack of data makes it difficult to determine whether these policies have resulted in a greater number of green roof projects. In Claus and Rousseau [52], a case study is used to show that the installation of a green roof is socially desirable, but private incentives (in Belgium) to invest are insufficient. Subsidy policies and governmental actions tend to be fragmented down to the municipality level, and information might be scarce. A more cohesive government policy is desired. Zhang et al. [53] study barriers to implement extensive green roof systems in Hong Kong. Eleven such barriers are identified by the authors, and ranked by respondents to a survey. The factor considered the biggest barrier is a lack of promotion/incentives from the government and social communities. The increase of maintenance costs is seen as a bigger barrier than the increase of design/construction costs. Skjeldrum and Kvande [11] identify building technical challenges related to the upgrading of roofs to blue-green roof systems. Key challenges are identified and listed via interviews with industrial and academic professionals in Norway. Snow and moisture challenges are identified as major points of uncertainty, but they are found to be solvable through planning and design.

It seems from the literature that two primary barriers to green roof implementation are economic uncertainty and building technical uncertainty. Economic incentives will mitigate the former to some degree, whereas the latter requires focused research that appear to be lacking as of the current, as described in this article. Risk identification and management policies are not well covered in scientific literature.

4.7. Regulations/Standards

Whereas articles in the Policies subcategory discuss the desirability of green roofs, this category describes legal matters, standards, and requirements concerning green roof implementation.

In Dvorak [54], the German FLL guidelines were compared to American standards on green roofs. The American standards and guidelines were found to be comparatively fragmented, with at least six different documents governing green roofs, and lacking in the fields of drainage media, growth media, post-construction testing, and root barriers, among others. Mees et al. [55] present a conceptual framework for discussing issues of the public-private divide in climate adaptation. The framework is applied to a specific case using green roofs as a stormwater management measure in Rotterdam.

In another article, Mees et al. [56] sum up green roof laws and incentives in European and American cities. Hierarchical arrangements (policies) are found to be the most effective for the implementation of green roofs. Edwards et al. [57] point out the lack of guidelines concerning certain specific aspects of green roofs. In particular, the lack of national standards in most of Europe (at the time of writing) is given special attention.

The German FLL guide to green roofs [9] is the only widely implemented green roof standard to date. Many other green roof standards are derived from the FLL guidelines, or refer heavily to them. An example is the Norwegian Standard NS 3840:2015 [13].

4.8. Insulation

The main themes appearing in this material include the heat flow through green roof assemblies, temperature measurements of the underlying roof membrane, and differences between summer and winter conditions.

Niachou et al. [58] provided the earliest case of green roof thermal measurements in the identified literature, conducted at a Greek hotel in 2000. While not a rigorous study, the conclusions are supported by later findings: Green roofs have marginal insulating effect compared to regular roof insulation, lower the indoor air temperature, and lead to modest energy savings. Exact values are not measured; however, later studies confirm the difficulty in quantifying these properties. D'Orazio et al. [59] measured the thermal properties of green roofs on a well-insulated building in a temperate climate. They concluded that the exact insulating potential is hard to determine, but there is some benefit to installing green roofs even on insulated buildings.

As thermal flow data are difficult to obtain from field tests, others have attempted to quantify the thermal properties of the growth medium itself in laboratory tests. Ouldbouhkitine and Belarbi [60] measured the thermo-physical properties of green roof substrate materials and plants, for usage in building simulation models. In Barozzi et al. [61], guarded hot plate and heat flow meter tests were carried out on 108 samples of growth media in the laboratory. Thermal conductivity (λ) was found to vary between 0.046 and 0.179 W/mK as a function of density, and between 0.046 and 0.470 W/mK as a function of moisture content (up to 50 weight-%).

In Coma et al. [62], five kinds of substrates commonly used in Mediterranean green roofs were dried and analysed. It was found that the λ value (denoted K in the original article) and thermal storage capacity varied between different substrates, but stayed well within the same order of magnitude (variation: λ: 0.138–0.199 W/mK, C_p: 724–873 J/kgK). Additionally, substrates with low organic content showed the highest rates of volumetric heat capacity.

Both Liu and Baskaran [63] and Teemusk and Mander [64] measured the membrane temperature on green roof plots. Both papers show that temperature fluctuations under a green roof are significantly dampened by as little as 50–100 mm of substrate. This helps preserve the roof membrane. Arkar et al. [65] also showed that the temperature under a green roof changes very slowly compared to the temperature on a reference roof in erratic ambient temperature conditions. These results are very relevant in a cold-climate context, particularly when considering the large number of freeze-thaw-cycles roofs are exposed to during spring and autumn.

The thermal performance of green roofs in cold winter conditions has been examined in a number of articles. In Liu and Minor [66], the thermal performance and annual runoff of two green roofs were examined and compared. The thicker roof (100 mm) had a greater impact on summer thermal flow due to its higher reflectivity, while the thinner roof (75 mm) was more effective in winter, owning to a polystyrene drainage board, as opposed to a semi-rigid polymeric board in the thicker roof. In Pierre et al. [67], Green roofs of two thicknesses (100 and 150 mm) were tested in sub-freezing temperatures against a heated roof in a hot-box. Adding a green roof increased the R-value for a roof from 2.82 to 3.7 m^2K/W (author's note: U-value from 0.35 to 0.27 W/m^2K). In Lundholm et al. [68], green roofs were found to yield a lower annual net heat loss than conventional roofs. Doubling the substrate thickness from 7.5 to 15 cm had no effect on net heat loss. Net thermal benefits of green roofs in winter is dependent on a variety of factors, such as substrate depth, species composition, or the exposure level of the roof. Snow acts as an "equalizer", lowering the relative benefit of a green roof.

Secondary effects of precipitation may also affect the thermal properties of green roofs. In Zhao et al. [69], it is found that the heat flux through a test green roof is reduced by approx. 23% compared to a conventional roof, but the difference is only 5% with a layer of snow on top. Preliminary results from the same measurements were also described in a 2012 article [70]. Tang and Qu [71] examine the effect of the phase change of water on the thermal properties of green roofs. It is found to reduce the heat loss by about 19% compared to traditional roofs. In Collins et al. [72], the thermal properties of green roofs in sub-zero temperatures and snow cover are tested. It is found that freezing the substrate actually decreases heat flux, due to a lower thermal bridging between frozen particles than in suspended water (bridge water effect).

In Scharf and Zluwa [73], the insulating properties of seven different green roof constructions in Austria were tested over a five-year period. U-values were generally (but not universally) higher (worse) in winter than in summer. The highest-performing green roof had a winter U-value of 0.3 $W/(m^2K)$, with a thickness of 300 mm.

It is evident that determining the U-value for a green roof is a difficult endeavour, and the actual value will fluctuate significantly depending on several factors, most prominently water content as shown by Barozzi et al. [61]. As shown in the studies described in this section, green roofs have a limited insulating effect, which becomes slightly higher when the roof freezes, but the overall insulation potential is both lower and less reliable than that of conventional roof insulation. Compared to the insulation levels required by Nordic standards, it is almost negligible. However, the insulating effect and thermal mass of a green roof will stabilize roof membrane temperature significantly, reducing temperature fluctuations as well as both minimum and maximum temperature amplitudes.

4.9. Pollution

These articles consider the effects of green roofs on pollutants in the air and runoff. A review by Rowe [74] encompasses published research on how green roofs can help mitigate pollution, how green roof materials influence the magnitude of these benefits, and suggests future research directions. Specifically, review categories are: Air pollution, carbon dioxide, fewer roofing materials in landfills, runoff water quality, and noise reduction. In Speak et al. [75], common green roof plants are planted next to a major road in Manchester, UK and sampled for pollutants. It is found that the selected plants can contribute to capturing airborne particles, and therefore act as a pollution filter in an urban setting. Grass roofs are reported to be more effective at capturing PM_{10} than sedum roofs. Teemusk and Mander [76] examine how green roofs affect the quality and quantity of rainfall runoff. Pollutants were found to accumulate in the substrate layer, but be washed out during intense rain.

All three articles appear to describe the same phenomenon. Green roofs will capture pollutants in air and rainwater. However, the pollutants do not appear to be stored in the roof permanently. Intense rain events may "flush out" the accumulated pollutants, making the runoff water more polluted. Note also that fertilizer used on the roof plants may be a water pollutant in itself.

4.10. Aesthetics

Aesthetics is a subjective matter, and as such all research on it found in this study was conducted using questionnaires and interviews. In White and Gatersleben [77], participants in a survey were shown photographs of buildings with and without greenery. Results indicate that the buildings with greenery where significantly more preferred than those without. Ivy facades and meadow roofs were rated the highest, while turf, brown, or Sedum roofs rated barely differently from bare roofs. The findings were claimed to be consistent with other areas of landscape research and the claims of the industry. In Fernandez-Cañero et al. [78], 450 respondents from Seville, Spain, were asked about their perceptions of green roofs. The survey shows that roofs with a greater variety of colours and vegetation were preferred over alternatives that are more «natural». Certain misconceptions about green roofs are also common, for instance that they lead to vermin infestations. In Jungels et al. [6], visitors to seven green roof sites in the US were surveyed about their aesthetic reactions to the roofs. Reactions and attitudes were largely positive, and negative reactions were mostly associated with perceptions of messiness. Sedum-dominated roofs blended better in with the roof than grass-dominated ones. Loder [79] studies the perceptions of green roofs among office workers in Chicago and Toronto. It was found that the respondents' geographical background played a key role in whether they preferred "meadow" or "prairie" green roofs, or whether the latter type brought positive associations.

It appears from all investigated articles that green roofs are considered more aesthetically pleasing than conventional roofs. However, opinions vary on the different plant mixes and patterns utilized.

4.11. LCC/Economics

Most articles in this section consider the question of Life Cycle Costs (LCC), Net Present Values (NPV), and payback times in a certain time perspective. However, economic analyses of singular green roof components have also been examined, as well as factors influencing the total economics of green roofs.

In Porsche and Köhler [80], the costs and benefits of different roof types (regular bitumen membrane, gravel roof, green roofs of various intensities) are summed up and utilized for LCC calculations. In Clark et al. [81], economical benefits of environmental benefits of green roofs are quantified and used in NPV calculations for an extensive green roof. Without such benefits, the NPV (cost) of a green roof is 20–25% lower than for conventional roof. Including the benefits, the figure is 25–40% lower instead. In Bianchini and Hewage [82], the cost, net present value, and payback time of two types of green roofs (extensive and intensive) are calculated. A probabilistic analysis gives a payback time of 4–14 years, depending on roof type. Green roofs are found to be a "low-risk" investment. However, this does not include any risks related to the green roofs themselves. Kim et al. [83] performed an LCC analysis of green roofs in South Korea. Green roofs are found not to be an immediately economically beneficial investment, but given the valuation of environmental benefits, they will be financially worthwhile, although by a small margin. Langston [84] discusses the cost-benefit balance of a green roof on a detached residential building in Queensland, Australia. It is found that, if built right, green roofs can be the least costly option for roofing in a 25-year perspective. In Mahdiyar et al. [85], the NPV and payback time of extensive and intensive green roofs in Kuala Lumpur are analysed. They are both found to be a low-risk investment, the extensive more so than the intensive. The payback time is found to range between four and six years. McRae [86] models the life cycle costs of a green and a conventional roof on a 100,000 sq. ft. building (location not specified) in a 25-year perspective. While the NPV of both roofs adds up to around a million dollars over the time period, the green roof ends up 0.5% cheaper, even without factoring in pollution or social benefits.

Mahmoud et al. [87] examines the energy and economic viability of green roof technology in the climate of Saudi Arabia. The annual energy consumption of a case building is found to be reduced from 169 to 110 kWh/m^2 with the application of a green roof on the entire structure. An NPV approach shows that the benefits of the green roof technology will only be realized towards the end of the life cycle of the building, because of the low cost of electricity in the country. While not directly applicable to a Nordic context, the article still raises an interesting point about how the abundance of one resource might reduce the economic gain of blue-green roof technology.

In Ichihara and Cohen [88], green roofs are found to increase rental prices in a (very high-end) apartment complex in New York City by as much as 16%. Results may be somewhat skewed by the high-end location of the complex. Wild et al. [89] compare and examine different attempts to evaluate the benefits of urban greening options and future development scenarios. The economic viability of two hypothetical future re-development scenarios were assessed. Results show that residents would be willing to pay more for greener infrastructure, but not necessarily enough to cover the costs for the developer.

In Niu et al. [90], various environmental benefits of green roofs are quantified, as well as energy savings and the impact on fees (i.e., stormwater fees) in Washington, DC, where the NPV of green roofs end up 30–40% less than that of conventional roofs, not counting green roof maintenance costs. The break-even point is estimated to be around 7 years. Peri et al. [91] examine the cost of disposal of green roofs. It is shown through a waste scenario that disposal costs account for roughly 4% of total green roof costs, of which 85% is made up of soil disposal. In Ab. Azis et al. [92], various building components and their effects on building value are examined (in a Malaysian context). Green roofs comprise only a small part of this study, but are found to be overall very beneficial to building value. In Peng and Jim [93], six climate-related benefits of green roofs are studied for the case of Hong Kong: thermal insulation, UHI mitigation, avoided upstream emissions of CO_2 and air pollutants, CO_2 sequestration, and air pollutants removal. Extensive green roofs are more economically attractive than intensive in terms of benefit/cost ratio and payback period. Payback period estimated to be 7 years for extensive and 19.5 years for intensive green roofs.

Most of the examined articles find green roofs economically favourable, mostly because of energy savings and the extended service life compared to conventional flat roofs. In addition, other effects such as biodiversity or improved sound insulation are found to be beneficial, but difficult to valuate. Green roofs also have additional value in their potential for increased rental prices. The energy payback period varies greatly depending on the local climate and the energy market. In Nordic cold climates, the energy savings from green roofs are negligible as shown in Section 4.8, suggesting that the side effects as mentioned above would contribute the most to green roof value. With these effects being difficult to quantify, the economic benefit of green roofs in Nordic countries is difficult to determine. Lastly, intensive green roofs may allow a building developer to utilize a greater fraction of a building site without violating green space requirements.

4.12. Management, Operations and Maintenance

These articles consider the various factors relevant to managing, operating and maintaining green roofs, including plant resilience, material usage, and maintenance schemes for operating green roofs.

In Butler and Orians [94], multiple plants are grown alongside Sedum, to assess whether the presence of Sedum will help the other plants survive water deficit. Using Sedum as "nurse plants", other species are found to fare better under water-deficit conditions. MacIvor and Lundholm [95] investigate the survival rate and hydrological performance of 15 different plant species on a green roof in Canada. The study suggests that in a coastal climate, native species may perform better than non-natives do. In Nagase and Dunnett [96], test plots for a green roof are sown on a roof in Sheffield in June. It was shown that a high sowing rate or a high watering rate is required for the plants to thrive during the crucial first year of operation. A somewhat unusual review by Wootton-Beard et al. [97] suggests improvement regarding the contribution of plant science to the role of green infrastructure. It is suggested that architects can look to plants for solutions for the management of light, heat, water, and CO_2 in buildings.

In Silva et al. [98], the maintenance schedules of eleven green roofs in Portugal were examined and documented through in situ surveys. Some anomalies were found, suggesting that not all maintenance plans were followed. The study also revealed that some design recommendations were not followed, particularly related to accessibility and fall protection measures. A review by Vijayaraghavan [99] provides an overview of green roof benefits, components, and shortcomings/constraints—most notably costs. Trends in the future of green roof implementation and research are summed up, and future research paths suggested. Vijayaraghavan points out that certain properties (such as pollution impact or acoustic properties) of green roofs have barely been investigated in literature, a conclusion in line with this article.

As recounted by Vacek and Matejka [100], mineral wool is used as a water storage medium in certain green roofs. The authors describe and test the degradation of the mineral wool after several months of use in a real green roof. It is noted that the uniform thickness and compression strength are severely compromised after only 16 months of use, and that roots will penetrate mineral wool layers 80 mm think or more. Viola [101] examines whether a newly patented polyurethane foam will be suitable for application as a growth medium in green roofs. Trials are carried out on site and in the laboratory. The material is found to be suitable, according to examined parameters, such as water storage capacity, plant survival, and ease of installation and inspection. Zirkelbach et al. [102] present a comprehensive hygrothermal model for green roofs, validated by field test results. Considerations of moisture conditions are limited only to growth and drainage media.

Overall, the Maintenance, Operations and Management aspect of green roof has been treated only indirectly in investigated literature. Silva et al. [98] is the most relevant article to this category, while many of the others could have been sorted into other topic categories.

4.13. Processes

These articles focus on the procurement process of green roofs, from questions of funding to design decisions. Two case studies are described in this category. Lindow and Michener [103] describe a real green roof retrofitting project, with a brief overview of most aspects to be considered, such as funding, design, and maintenance. While not making any groundbreaking new discoveries, it nonetheless provides an excellent overview of factors and aspects to be considered, such as building code issues, specifications in a bid document, a constructability review, and arrangements for the long-term operation of the green roof. The article also lists the practical lessons learned from the building project. Nektarios et al. [104] documented the intensive green roof above the extension of the Athens Concert Hall, and the various substrates, drainage systems, and substrate stabilization systems utilized.

In Grant and Jones [105], a framework for evaluating green roofs is described, combining green roof characteristics from the FLL guide with the Choosing by Advantages model. A test of the framework could unfortunately not be completed. In Brudermann and Sangkakol [106], an analysis on green roof strengths, weaknesses, opportunities, and threats (SWOT analysis) is performed on green roofs, and interviews with industry experts are conducted to perform an Analytical Hierarchical Process ranking of green roof aspects. It is found that the positive aspects of green roof generally outweigh the negatives. The most important single factors were flood risk reduction, environmental benefits, and the influence on green politics/strategies in cities. Wong et al. [107] examine the factors that are important in enhancing green procurement in the construction process. The top three most significant factors identified are mandatory environmental regulations by the government, client requirement in tendering, and government/NGO requirements. Note that the used definition of "green procurement" does not necessarily involve green roofs.

4.14. Others

The articles listed here did not fit into any of the categories listed above, yet were considered relevant enough in the climatic scope of this study to be included. In these cases, there were not enough articles on the same subject to create new categories.

Both Köhler and Poll [8] and Jim [7] concern the history of green roofs. The former describe old tarpaper green roofs (TPGs) in Berlin in comparison to modern extensive green roofs. The latter provide some historical context to the origins of green roofs and compare ancient and modern building practices.

In Tsang and Jim [108], a stochastic model is made to estimate the demand for green roofs and how to optimize inventory to meet it efficiently. The findings suggest adopting the safe lower limit of demand fluctuations to prevent overstocking.

Xiao et al. [109] gives an overview of green roof benefits and construction techniques used in China, as well as of Chinese research into the field. Thodesen et al. [2] provides a review of the research into the effects of Nordic climates on extensive green roof selection and performance.

Hoskins and Homer [110] consider structural implications of a refurbished green roof in a fire scenario. The extra weight of the green roof will lead to collapse significantly earlier than assumed for the original structure. Some practical implications for firefighters are also considered. In Galbrun and Scerri [111], green roof samples are tested in an acoustic laboratory. Generally good sound insulation properties are documented, depending on the features of the roof.

5. Discussion

This paper set out to address:

1. What are the main areas of research concerning green roofs in temperate to cold climates?
2. What are the main challenges investigated?
3. What are the main knowledge gaps?

From the researched literature, two main subjects have been given the most attention: The first is the thermal flows through the green roof envelope, and the implications of this for energy usage and associated economic benefits. The subject has been approached from a variety of angles, all mostly concluding that green roofs reduce building energy consumption, but that the benefit is smaller for well-insulated buildings in cold climates.

The other main subject is the hydrological behaviour of green roofs for the management of stormwater. However, the research on water management appears to end at the drain of the roof. It might be that the flow of water into the drains and from there to ground level is treated as a building design problem, but it is still peculiar that no article considers what happens to water downstream of the green roof assembly. Keeping drains and downpipes functional over time is a vital part of green roof operation, but it is not mentioned in the investigated literature. It may be assumed that drains, pipes, and overflow solutions are the same for conventional and green roofs, however this assumption appears not to be backed up by any research data. Additionally, experimental roof setups tend to be more closely monitored and better tended to during operation than green roofs in service.

The economic component of green roofs has been reviewed by multiple sources, which stress that this is dependent on local economy and climate conditions. In hot climates, the evaporative cooling effect of green roofs is desirable and leads to significant savings on air conditioning, however, this effect appears to be less pronounced and less sought after in cold climates. The magnitude of this cooling effect has not been researched thoroughly for cold climates, signalling a knowledge gap in research literature.

No scientific articles dealing with end-of-life building technical conditions of a green roof were identified. Full-scale green roofs are underrepresented in literature, with only three investigated papers considering green roofs not built specifically for research purposes, and being older than two years at the time of research. This shows a great disparity between green roof research and construction. There exist plenty of green roofs of advanced age all over the world, but this study suggests that nobody are conducting research on them. Conversely, in the vast majority of cases, green roof research is conducted on test plots or roofs that are not (explicitly stated to be) intended to remain in place beyond the duration of research. In other words, there is a clear lack of research on green roofs that are actually meant to serve as building roofs throughout their lifetime. The two articles in maturity category 6 (green roofs built for research, but intended to remain in place after research is over) both concern the same roof [64,76]. With the large number of green roofs in existence worldwide, it is reasonable to assume that a significant number of them will be put out of service and disposed of every year. Academic actors in the field should keep a look out for renovation/rebuilding projects involving old green roofs, as this would present an opportunity to examine how the roof has operated and aged.

This lack of data regarding long-term operation of green roofs may be considered the largest knowledge gap uncovered in this study. Very few of the roof assemblies investigated in literature have been full-scale roofs serving a building under realistic operating conditions and maintenance schedules. As such, certain considerations and aspects of long-term green roof operation has summarily been ignored. For instance, the risk aspect is rarely brought up in scientific literature. Hoskins and

Homer [110] address challenges in case of fire, and Skjeldrum and Kvande [11] mention moisture problems, but no comprehensive article has been written on risks specifically.

Aside from operational issues, research literature also has gaps concerning the design- and decision-making processes of green roofs. The benefits of green roofs are well documented, and it is evident that numerous green roofs are being built all over the world, but the process of green roof acquisition in practical cases is not documented in research literature. This is especially puzzling considering the large number of implemented green roofs worldwide, as procurement and design processes must necessarily have been undertaken for every single full-scale green roof ever built.

6. Conclusions

In sum, it is shown that the physical properties of green roofs have been thoroughly explored in literature, with only a few knowledge gaps relating to green roof performance in cold climates. For instance, the exact values of green roofs' insulation effect remain difficult to determine. However, it is agreed that green roofs will reduce thermal flows through the roof construction, albeit to a small degree in well-insulated buildings, and even less so in cold climates. The energy savings in Nordic conditions can be said to be negligible. However, the reduction of temperature fluctuations at the roof membrane, compared to a non-covered roof, will extend the service life of the membrane.

It is also fairly well documented in literature how green roofs—even those not specifically built for it—provide an efficient method of stormwater management, both reducing and delaying peak flows in water runoff, as well as reducing the overall amount of runoff from the roof through evapotranspiration. Research has been conducted in multiple climates worldwide, including cold climates.

However, the study also shows that green roof research for the most part is limited to single properties studied in isolation, and that issues relating to actual implementation of full-scale green roofs have hardly been described in research literature. The risk aspects of green roof operation do not appear to have been researched beyond superficial considerations, although more comprehensive risk analyses might have been performed by industry actors during full-scale green roof construction projects. However, no framework for green roof risk analyses have been found by the authors of this article, which presumably indicates that the construction industry is also lacking such a framework. This again implies that green roof implementation is evaluated on a case-by-case basis in the industry, or a company-by-company basis at best. More research is required on the technical implementation, long-term operation, and management of full-scale green roofs, to standardize procedures in the field and thus ease implementation.

Future work on the subject of green roofs should attempt to bridge theoretical and practical considerations. The investigated properties of green roofs must be verified through full-scale operation, where practical challenges must be uncovered, described, and solved. A complete framework of green roof design and operation should be developed, turning blue-green roof construction from novelty to a routine act. For the documented benefits of green roofs to be realized on a large scale, they have to be implemented on a large scale, and for that to happen, the practical considerations need to be addressed.

Supplementary Materials: The following are available online at http://www.mdpi.com/2075-5309/8/4/55/s1, Spreadsheet of examined literature (Excel file).

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Paper 3

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Perspectives on Quality Risk in the Building Process of Blue-Green Roofs in Norway

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Perspectives on Quality Risk in the Building Process of Blue-Green Roofs in Norway

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Abstract: As climate change brings an increase in torrential rain events in Nordic climates, new technologies are developed to manage stormwater. Blue-green roofs are constructed as a means to reduce the runoff of stormwater from roofs and reduce the risk of urban flooding. However, compared to conventional roofs, blue-green roofs represent different construction and operation conditions, which may affect the long-term integrity of the roof. The purpose of this research is to understand the variety of perspectives on how different actors perceive and manage quality risks related to blue-green roofs—that is, the probabilities and consequences of defects. The quality risks of blue-green roofs have been investigated through document studies and interviews with actors in the Norwegian building sector. Data have been collected from actors across the building sector to map differences in how risk is managed from several perspectives. The findings show that actors view quality risk in very different ways. While building owners are primarily concerned with the quality of the finished product, the primary concern of other involved actors may be to ensure that eventual defects cannot be attributed to their own activities. The efforts of the various actors to reduce the risks in their own activities may not necessarily reduce the risk of defects in roofs. To ensure a more comprehensive management of quality risk in blue-green roofs, it is necessary to consider the perspectives and incentives of all involved actors. This way, a framework could be developed as a feasible tool in blue-green roof projects.

Keywords: risk; blue-green roof; building process; quality risk; climate adaptation

1. Introduction

The densification of cities causes an increasingly large fraction of the ground surface to be covered by impermeable materials, leading to a greater risk of stormwater flooding [1]. In certain climates, this risk is exacerbated by climate change, for instance, in Norway, where an increase in torrential rain events is forecast in the future [2]. To a greater degree than ever, it is necessary for cities to address the threat of urban flooding through effective stormwater management. In addition to the threat of urban flooding, buildings also need to be made more resilient in general to face the challenge of a changing climate [3,4]. In sum, the future climate requires a better understanding of risk and how to handle risk in the built environment. In this paper, the investigated risk perspective is that of quality risk, the term being understood as "the likelihood and consequences of building defects occurring".

A blue-green roof is a roof assembly where rainwater is stored using plants and various substrate layers. The difference between an ordinary green roof and a blue-green roof is that the latter is purpose built for stormwater management purposes. This might include a larger water storage capacity than what is needed for the plants to survive [5]. Blue-green roofs are found to have considerable potential for stormwater control within a building site, both when applied in new buildings or retrofitted onto existing buildings [6].

In practice, the reasons why blue-green roofs are chosen in a given project can be divided into two categories: those instances where the initiative is taken by the project owner, or those where blue-green roofs are built to satisfy external (i.e., legal) requirements. Until recently, green roofs have tended to be built for reasons related to the former category. They were typically considered a novelty and chosen for aesthetic reasons, to add an element of greenery to a building [7–9]. The stormwater management properties of the roofs were largely seen as an optional bonus and rarely considered in the stormwater management plan (although this has been a motivation in certain projects). However, in recent years, new requirements for stormwater management have become stricter in Norway as well as many other countries. International research has documented the benefits of using green roofs to reduce floor risk in urban areas [10–13]. In Norway, rules on a regional or municipal level are mandating the use of solutions for detention, retention, and local infiltration of stormwater, as shown in [14,15]. Green and blue-green roofs see increased interest as a measure for stormwater management in urban areas [6]. This could lead to an increased use of green roofs in building projects, without an owner-driven initiative for their construction. As blue-green roofs become more common, it is vital to understand the risks they may pose for the buildings on which they are built.

Blue-green roofs are commonly built on top of a conventional, compact, flat roof assembly [16]. Many of the risk factors associated with blue-green roofs will also be relevant for compact flat roofs. Therefore, this article will also include risk factors for compact flat roofs, as the volume of literature available on these roof assemblies is substantially greater than that on green or blue-green roofs.

It is known from experience that roof defects are a recurring problem in the building stock today [17]. Comprehensive, quantitative data on the prevalence of building defects are, however, not available [18]. Attempts to establish a common Norwegian national database for building defects have so far failed. Research suggests that the most commonly investigated roof defects in Norway concern the intrusion of rainwater or snowmelt into the building structure. Gullbrekken et al. [19] found that roof defects comprise 22% of building defect cases in Norway, with precipitation damage occurring in 51% of cases of flat roof defects. Moisture damages (all moisture sources) accounted for 89% of all investigated defect cases for flat roofs. Moisture compromises the insulating capabilities of building insulation, may stain materials, and facilitates the growth of fungi.

It is specified in the Norwegian technical regulations for buildings that moisture intrusion must not occur in such a way that the building may be damaged [20]. The requirements are function-based and independent of the solutions chosen to meet them [21]. This approach gives designers wide freedom to choose a solution, but also increases the room for error. A means to reduce the risk of error while retaining the freedom is therefore highly desired.

A building project involves several actors, each responsible for a share of the final product. For large building projects, the organization may be very complex. It is not always clear to everybody where the borders of responsibility go between actors. Additionally, actors may perceive risks and challenges differently. This may potentially create borderline cases where defects occur because nobody considered the quality risk of the chosen solution. A clear mapping of the overall risk picture for quality defects is therefore required, including collecting the perceptions of risk from the various involved actors. In light of this complex problem, this article investigates the following research questions:

- How do the various actors in the building process perceive the risks of blue-green roofs?
- How are the risks associated with blue-green roofs currently managed?
- How can the management of quality risk be improved?

The following limitations apply to the research: only the perspectives of certain actors involved in a building project are investigated, further detailed in the Methods chapter. Natural hazards are not included. Positive risk (beneficial uncertainty) is not considered. The investigated time period is between conceptualization and handover of the building, excluding the operations/maintenance phase or end-of-life.

2. Theoretical Framework

2.1. Blue-Green Roofs

Blue-green roofs are roof assemblies wherein a mat of vegetation and its substrate layers are used to store precipitation water, making the roof part of a stormwater management strategy. Any green roof built for this purpose can be considered a blue-green roof [5]. In Norway, climate change is expected to cause an increasing frequency of extreme precipitation events [2], which may lead to flooding in urban areas. Using roofs to manage stormwater is an important part of the strategy to combat urban flooding [6]. A blue-green roof will add retention capacity (evapotranspiration of water) to the detention capacity (temporary storage of water) provided by conventional green roofs [12,13].

A green or blue-green roof assembly consists of various layers, typically constructed on top of a conventional compact roof structure [22,23] (Figure 1). Plants, commonly sedum or other succulents, grow in a substrate and form the outer roof surface. A sheet of geotextile separates the substrate from the water storage layer, which commonly consists of extruded plastic boards or crushed Leca. The water storage layer is designed not to give a standing water pressure against the roof membrane, by storing water in cups, boxes, or capillary pores. The layer also provides drainage for excess water. A root barrier is applied against the roof membrane to protect it from root damage; this may also be achieved through chemical treatment of the roof membrane itself. Optionally, the plants and their substrate can be replaced with a permeable pavement, to create a so-called "blue-grey roof" [24].

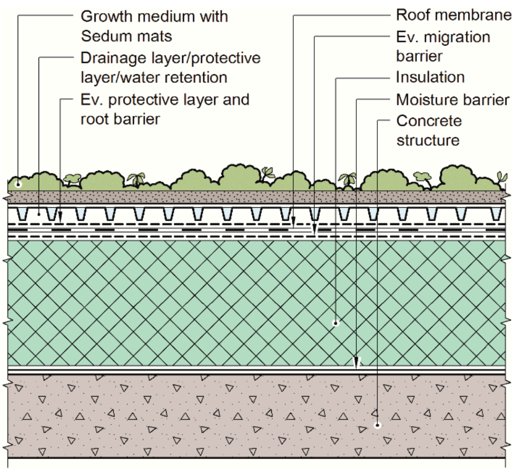

Figure 1. Example of a blue-green roof assembly. The thickness of the growth medium may be vastly increased for intensive green roofs. The water storage and drainage layer shown is based on extruded plastic boards, but this layer may also consist of gravel or crushed baked clay. Alternate concepts for blue-green roof assemblies also exist, see, for instance, Ref. [12]. Illustration ©SINTEF.

Adding additional layers onto the roof assembly will change the physical operating conditions of the roof membrane, which is the watertight layer that keeps moisture out of the building envelope. Parameters such as moisture, temperature, solar irradiation and mechanical pressure will be very different for a roof membrane lying underneath a blue-green roof, compared to exposed roofing. In certain aspects, these conditions can be beneficial for the long-term integrity of the roof, particularly the reduced temperature fluctuations and solar irradiation [23,25,26]. As such, the economic benefits of green roofs have been the focus of much research. However, the building technical aspects of green roofs have not been well studied in research literature [5]. The physical operating conditions of blue-green roofs are very different from conventional roofs, with associated risks that must be managed. Crucially, the roof membrane will not be available for inspection after the green roof is constructed, and repairs to the roof will subsequently be vastly more expensive and difficult than is the case for conventional roofs. If there is a defect in the water-proofing layers, it is likely not to be discovered until water has penetrated the whole roof and soiling can be seen inside the building. By then, the defect may have caused significant damage, which is expensive to repair, and it may be difficult to find. However, if the roofing layer is intact when the roof is finished, it is likely to remain intact as the blue-green layers offer some protection from weather and wear. It is therefore of vital importance that the roof is properly designed and constructed, and that its integrity is secured throughout the construction period. Risk factors threatening the quality of the roof must be mapped and made known so the risk can be reduced.

2.2. Risk and Quality Risk

Risk is commonly understood to mean the negative consequences of uncertainty, that is, the probability of negative events and their consequences. A more formal definition suggests that "Uncertainty is an event that, if it occurs, has a positive or negative effect on a project's objectives" [27,28]. There are several types of risks, used in different contexts. It is the impression of the authors that risk management literature tends to focus on risk in terms of physical hazards, schedule delays or cost overruns. Taroun (2014) sums up the traditional risk perception in the construction industry as "the variance of cost and duration estimation" [29]. Quality can be defined as "meeting the legal, aesthetic, and functional requirements of a project" [30]. "Quality risk" is a term here used to describe the likelihood and consequences of building defects occurring, rather than the effects of defects on the project's schedule and cost.

However, the term "quality risk" is not well defined in literature. Other terms found to describe the same subject include "defect risk" [31,32], "quality management" [30], "quality deviations" [33] or "defect management" [34]. In the following, we use "quality risk" to include all of these terms. Defects include design flaws, build flaws, material flaws, accidental damage, gradual degradation, and use flaws. The latter two categories of defects occur during the use phase of the building (barring exceptionally long construction periods) and are excluded from the scope of this article. It has been estimated that defects account for 2–6% of the cost of production of a building [35].

Quality risk is a type of risk whose primary consequences are usually restricted to the building itself, or to its occupants in rare cases of catastrophic failure. Although the costs associated with quality failure can in some cases be divided, shared, or shifted onto actors in the construction process [27], the defects themselves and their consequences cannot be taken out of the building. In a sense, the building itself is the primary stakeholder when it comes to quality risk. For all the other involved parties, quality risk must be seen in relation to financial risk. The reduction of quality risk is a benefit that will have to be weighed up against its costs. Most of the parties involved in the building process are not likely to be directly impacted by building defects but will instead incur costs of repairs and/or compensation for defects for which they are found responsible. It follows that there are two ways for an actor to manage quality risk: avoiding defects or avoiding responsibility.

2.3. The Building Process

A conceptual illustration of the building process and its main involved actors, exemplified in a design–build (DB) delivery model, is shown in Figure 2. As the figure shows, actors may be directly involved in the production organization of the specific project, attached in a more peripheral fashion in the supply chain, or influencing the project by laying premises or legal frameworks. Different actors are involved in different phases of the project, and there may not be direct communication between all the actors. However, decisions made by one actor early in the process may influence other actors in later phases. For instance, contractors build according to plans submitted by designers. Likewise, premises and conditions set by actors involved late in the process may influence the decisions made in the early phases. For instance, materials chosen by the architect need to be available for the supplier to deliver.

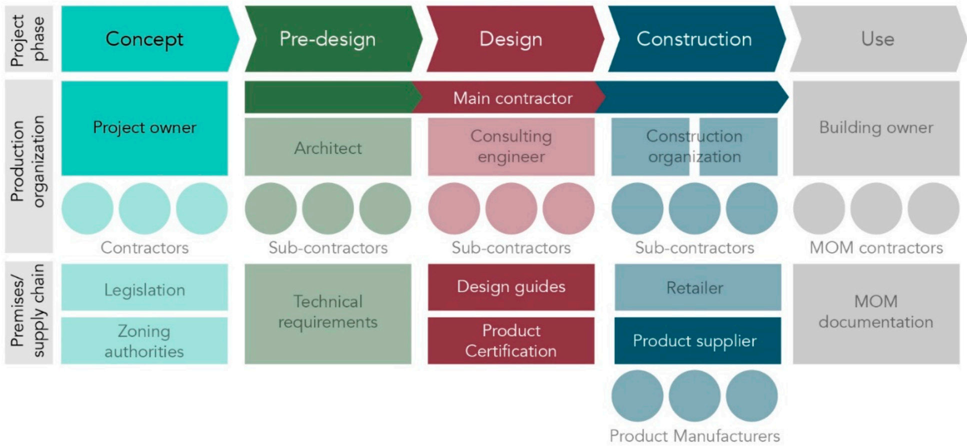

Figure 2. Illustration of the building process and its main involved actors in a design–build (DB) contract delivery model. Actors and phases considered outside the scope of this article are shown in faded colors. The inclusion of actors in this article represents all project phases until the point of handover, and actors both within and outside the production organization. The split boxes under "construction organization" denote a larger organization with more sub-contractors than what is common in the other phases.

2.4. Actors in the Building Process

The sections below outline the main actors in the building process and their general roles in a project, as shown in Figure 2. While there may be variations depending on the delivery model for the project, the tasks performed by each actor do not usually differ significantly from what is listed [36].

2.4.1. Project Owner

The project owner initiates and conceptualizes the building and will in many cases end up owning it upon completion. The project owner has a governing task of deciding the mission, goals and organization, and a supporting task of providing resources and enabling formal decisions [37,38]. Defects that occur during the operations phase, or that are discovered after the contract warranty period, will be the responsibility of the building owner, and as such the owner carries the greatest quality risk. The long-term integrity of the roof is therefore a key point of interest for the building owner. As the owner also initiates the project, they will be able to influence the roof concept to a significant degree through the tender process, by choosing pre-design specifications (beyond what is mandated by technical requirements), or through contract design.

2.4.2. Designer/Architect

One of the main functions of the design phase is for the owner to communicate to the designers his or her needs and objectives in initiating the project [39]. For a construction project, the designers are the architects and engineers responsible for detailed design. They are responsible for transferring theoretical and practical expertise into the building project, to ensure that the chosen design conforms to all relevant regulations and standards. The designer and/or architect carry the responsibility for design flaws, so it is in their interest to ensure that their recommendations adhere to the best possible practice.

One way to document best practice is to anchor the recommendations in design guide documents issued by third-party advisory bodies. These may be governmental bodies, academic institutions, industry organizations, or independent associations. In Norway, the research organization SINTEF develops building design guides through its subsidiary SINTEF Community. The design guides are widely used and enjoy a good reputation throughout the Norwegian construction industry [40,41]. The solutions are based on the best practice from the construction industry and independent forefront research.

2.4.3. Contractor

The role of the contractor depends on the type of delivery model applied in the project in question. The most common delivery models in Norway are design–bid–build (DBB) and design–build (DB). In a DBB model, the contractor is engaged by the project owner after the building has been designed by architects and engineers. The contractor will then construct the building according to the given plans and blueprints. Moreover, in DB contracts, the design responsibility is delegated to the contractor, as shown in Figure 2. The contractor is engaged after the owner has drawn up pre-design requirements for the building, whereupon the contractor is responsible for the design process as well as constructing the building [42]. For the owner, the change from DBB to the DB model will mean less liability towards the contractor for design documents. As a result, the owner's risks, and, consequently, the potential contractor's claims, will in theory be mitigated substantially [43].

Making constructability knowledge accessible to the designer(s) and/or architect(s) and at an appropriate level of detail at the right time in the design process is a significant opportunity to improve the constructability of design [44]. Therefore, to mitigate quality risk in the building process of blue-green roofs, the contractors should be allowed to contribute with their constructability expertise in the design process of the project. Methods for employing the full potential of constructability expertise from all sources (including specialty contractors) exist in the use of integrative/collaborative mechanisms [45]. This may be achieved in practice through implementing a collaborative project delivery method that seeks to create an effective integrated team through early involvement of the contractor along with a team with the right expertise seeking to take full advantage of the team's collective 'knowledge pool' [42,46].

2.4.4. Material Supplier

As a construction project is a temporary construct that produces a one-off product, its construction supply chain is characterized by instability, fragmentation, and by the separation between the design and the construction stage [47], Typically, products are chosen by the contractor based on recommendations from the design phase. The supplier does not typically participate in a project organization, but the performance of their products needs to match the documented specifications. Defects in materials occur when the operating conditions they are subject to exceed the performance limits of the material. This can occur through improper use of the material, if the operating conditions are more extreme than anticipated, or if the performance limits of the materials are lesser than documented [48]. In the latter case, defects will be the responsibility of the material suppliers. To reduce the risk of defects, suppliers therefore aim to document the performance of their materials as accurately as possible. The performance parameters of materials are determined by methods specified in industry testing standards. The material supplier may also reduce the risk of improper use through supplementary product documentation, such as installation manuals or maintenance plans, or by training workers.

It is also possible for a supplier to enlist a third-party body to independently verify the product's performance and compliance with the building code, and overall assess its general suitability as a construction product. The product can then be certified with a technical approval if it meets the criteria. A technical approval is additional documentation beyond what is required for CE-marking (European standards conformity marking). Institutions offering such certifications include SINTEF (Norway), RISE (Sweden), TÜV (Germany) and BBA (UK). Certifications include testing according to the aforementioned standards, as well as independent assessment of the product's properties [49].

However, when a material property is declared using an industry standard, for instance, dimensional stability or tear strength, the declared performance limit is not necessarily universal. The given property represents the performance limit of the material when subject to the test specified in the standard. While standardized tests aim to reflect realistic use cases, this may not always be possible in practice. For instance, the testing standard for root penetration through roofing membranes presumes one specific plant that may not be commonly found on blue-green roofs [50].

2.4.5. Other Actors

Aside from the main actors listed above, a handful of other actors can be said to be involved in a building project, if only in a tertiary fashion:

National construction authorities shape and enforce national building regulations, which also yield a large influence on the building. These technical regulations concern structural safety, universal accessibility, energy requirements, fire safety, and other technical requirements the building must conform to [51].

The local construction and planning authorities give the premises for initiation of the project. Local laws may yield great influence on the chosen solutions for the building, primarily through zoning regulations that govern matters such as the building's height, footprint, or placement, but also the building's connections to local infrastructure. For instance, local stormwater management practices may demand that roof runoff water is infiltrated into the soil within the borders of the property [14]. Such a requirement makes internal drains unfeasible, but external drainage solutions from flat roofs may have issues with snowmelt re-freezing. This balance between stormwater management and building physics is currently a challenge under further investigation [52].

3. Methods

The research has been conducted in several phases, described separately in [53–56]. The methodology includes interviews with actors from several parts of the Norwegian building industry, searches in the national database for building tenders in public construction projects, and two document studies. The results of each study phase are here compared to form an overall impression of risk management of blue-green roofs in the Norwegian building sector. As the building process is complex and involves more actors and perspectives than could reasonably be studied in full given the available time and resources, it was decided to single out a limited number of actors for further study. It was decided to focus on the project owner, contractor, supplier, and design basis guidelines to get representation from each step of the building process as illustrated in Figure 2. The selected perspectives include actors within the organization of an individual building project, as well as actors that influence the project without (necessarily) participating in it. Every phase of the construction project until the point of handover is represented.

3.1. Interviews—Overview of the Problem

The first phase of the research was focused on collecting data on risk elements regarding blue-green roofs. As they are usually built upon compact, flat roofs, they share many of the same risk elements. It was decided to find out to what degree defects in compact roofs were occurring in Norway. However, comprehensive quantitative data on building defects in Norway do not exist. Certain companies in the insurance industry, or some advisory firms, maintain their own databases based on cases the company has been involved in. However, these databases are not synchronized and not comprehensive. There exists a mandate for the National building council to create a national database of building defects, but it is yet to materialize [18].

As such, qualitative data had to be gathered instead. A qualitative approach appears to be a common method to study building defects, as quantitative data is not available. Examples are found in [35,57]. To map which types of roof defects are the most prevalent in Norway and how they occur, interviews were conducted with experts on compact roofs from the Norwegian building sector. A total of 7 people were interviewed in 5 separate interviews, comprising property developers in the public sector, an insurance agent, a representative from a government agency, and a materials supplier. Limiting the number of interviews allowed for a deeper analysis of the contents of each interview. Thus, the emphasis was on conceptualization through generating a richly textured understanding of experience rather than seeking to “frame” or “contextualize” the sample size [58,59]. The interviews were carried out over the phone or in person. An interview guide was developed and made available to the interviewees prior to the interviews. The guide helped structure the interviews, which were designed to be loose to allow a natural flow of conversation. The interviews were recorded and transcribed, so as not to interrupt the conversations.

3.2. Public Tender Database—Project Owner Perspective

This research phase aims to map to what degree the owners in public projects are making use of their influence in the concept/pre-design phase. To investigate how project owners manage risk in green roof projects, it was decided to examine the specifications given for green roofs in construction tenders. The Norwegian public tender database, Doffin [60], was searched for mentions of the phrase “green roof”, yielding four results from recent projects that were further examined. Additionally, the building division of a municipality near Oslo was contacted to obtain the pre-design reports for known construction projects that included green roofs; this yielded a further three results.

The seven project tenders were examined to determine the contract design, the intention behind building a (blue-) green roof, and the relevant project phase. Where technical documents were available, the level of technical specifications in documents was investigated. This included, e.g., the type and placement of the roof membrane, the stormwater management function of the roof, the location and type of drains, references to roofing integrity, or other mentions of specific risks. This made it possible to assess the overall thoroughness of risk management from the project owners’ side, in the phase where they yield the greatest influence over the project.

3.3. Material Supplier Datasheets—Supplier Perspective

Risk management on the part of the material supplier was examined through an investigation of product declarations and documentation, specifically for roofing membranes. The research phase aims to chart the documentation required to fully understand the characteristics of a given product, to assess its suitability for a given construction project. Several products available on the commercial market were singled out for study through data sheets, assembly instructions, and, where available, technical certifications from third parties. Documents were searched to map which standards the products conform to, describing how the material properties were determined.

3.4. Building Design Guides—Advisor Perspective

The design of buildings in Norway is greatly influenced by design guidelines developed and published by SINTEF Community, formerly the Norwegian Building Research Institute. More than 800 design guides exist, covering every phase of a building’s lifetime and every part of the building structure. Issuing such detailed recommendations gives SINTEF Community a certain level of responsibility in building defect cases, putting them at risk of receiving the blame if a recommended solution turns out to be faulty. For this reason, the recommendations in the building design guides are periodically thoroughly reviewed.

To investigate how the SINTEF Building Design Guides manage quality risk in practice, 9 design guides pertaining to green roofs and compact roofs were examined. There are four levels of recommendations in the design guides, ranked by decreasing strictness as follows:

- Required by law, mandatory (i.e., fire safety measures).
- Strongly recommended (i.e., moisture safety measures)
- Recommended (i.e., measures for building longevity)

- Optional (i.e., aesthetic measures)

The number of recommendations of each level in the nine design guides was counted. Explicit mentions of quality risk issues in the design process were also noted, to count how directly quality risk is considered in the Building Design Guides. A small literature search was also conducted to examine information overload in a design project and the limit of effective information processing in the human brain.

3.5. Project Delivery Methods—Contractor Perspective

The management aspects of flat-roof construction were studied qualitatively, described in Section 3.1 [54,61]. While not being examined directly, the project delivery methods have been shown to have an immense effect on how risk is perceived, managed, and allocated in projects. The concept of collaborative project delivery methods was examined in a separate scoping review, assessing 156 articles concerning Partnering, Integrated Project Delivery, Alliancing, Relational Contracting, and Relationship-Based Procurement [62]. The role of the contractor has also been examined empirically through case studies [42,46].

4. Results

4.1. Summary of Main Findings

A summary of the main findings of the study presented, through the perspective of actors shown in Figure 2, is given in Table 1. In the table, the advisory body and product certification function have been merged.

Table 1. Summary of the main findings. The column "Identified measures" refers to measures discussed in the Discussions chapter, Section 5.3 of this article.

Actor	Examined Project Phase	Risk Avoiding Factors	Risk Management Factors	Identified Measures
Project owner	Concept	• Delivery below expected quality • Design flaws	• Specifications in tender documents • Contract delivery model	• Cooperative delivery models • Demands of contractors • More detailed specifications in tenders
Main contractor	Pre-design, design, construction	• Exceeding budget/schedule • Defects occurring on site	• Coordinating actors on site	• Delivery models • Structured production organization
Advisory body (design guides, certification)	Design	• Design flaws • Material flaws	• Design guides • Certification documents	• Establishing risk hierarchy • Stratifying design guidelines
Supplier (product data sheets)	Construction	• Material flaws causing building defects	• Product performance declarations	• Practical instructions • Participation in project organization

4.2. Interviews

When interviewed about the nature of roof damages, respondents mentioned challenges both on a physical and processual level. A general trend in the interview responses was the observation that complex roofs are more challenging than simple surfaces. Complex geometries, corners, transitions between building elements, and perforations of the roofing for technical equipment were all seen as challenging to work with and prone to defects. When a building is expanded and the new roof is joined to the old building, it is difficult to verify the integrity of the seam. It was also observed that material defects appear to be a rarity, with materials generally delivering on their specifications. Improper design or installation is a more common cause of defects. Design errors and build errors were thought to be equally common. Counterfeit or sub-standard materials (CFSS) were not considered common in Norway. Only two of the respondents had ever heard about cases involving CFSS. Fraudulent workmanship is thought to be a bigger problem than fraudulent materials. However, the subject is not given much attention and it may be a more common phenomenon outside the professional market.

On a processual level, the respondents stressed the challenge of cost versus quality. A system of technical approvals for materials is used to certify compliance with standards and to document that a product is usable in a Norwegian context. However, there appears to be a sentiment that any product with a technical approval is as good as any other, so builders tend to choose the cheapest option if several are available, regardless of their technical specifications. However, technical approval does not automatically mean that the product is suitable in a specific project. For instance, wind loads vary greatly between locations, and roofing may be torn off if it is not rated for the design wind loads.

Building owners generally expressed a large amount of trust in their contractors. Large, public building owners may have long-term agreements or partnerships with construction companies for construction and maintenance of their buildings. This is a measure to save cost, but also reduces the risk of fraudulent workmanship in the project. Construction companies may also partner with suppliers, creating a chain of agreements between large, professional actors in the building sector. However, in the "consumer construction market", between smaller and less professional actors such as homeowners or small businesses, relations may be less formal and less anchored in solid contracts. It is, however, challenging to acquire an overview of this sector.

Respondents also noted that errors in the use phase could lead to roof defects. Typically, this included flawed maintenance or lack thereof entirely. However, the use phase is to be considered outside the scope of this article.

4.3. Public Tender Database

The majority of the case projects (five out of seven) concerned calls for design–build contracts. Little consistency was observed in terms of risk management in the available documents. In three of the cases, a green roof was only mentioned as an option in the contract tenders, with no further technical specification. This leaves the design of the blue-green roof to the contractor, without additional input from the owner.

Where technical documents were available (four of the seven cases), the level of given specifications was not consistent. Pre-design reports mentioned the green roof in all cases, but the level of detail varied between them. Only two pre-design reports specified the design of the roof layer. Only one report recommended that the roof undergo an integrity test before the green roof was assembled. References were found to further literature (SINTEF Building Design Guides [22]) in several cases, but the guides do not necessarily cover special use cases such as transitions between building elements.

The thoroughness of both the tenders and the pre-design reports appears to depend entirely on the persons who wrote them. There does not seem to be a framework to follow when specifying technical details on this level of the building process, where owner input has the greatest possible influence on the finished product. As a result, the application of this influence by public project owners is inconsistent at best and absent at worst.

4.4. Product Datasheets

The performance declarations of the investigated roof membranes listed different parameters according to 18 different standards; however, not all standards were used by any one product. One product declared properties in accordance with 13 standards, others used as few as seven. These standards are in turn referencing other standards. The standard EN 13707:2013 Flexible sheets for waterproofing–Reinforced bitumen sheets for roof waterproofing–Definitions and characteristics [63] lists 23 other EN and ISO standards as "indispensable for its operation". Additional documentation was also available through product certification and assembly instructions.

This research phase concludes that an understanding of a product's performance parameters and hence an assessment of its suitability for use in a single project requires in-depth expertise or a significant investment of time and resources. Access to all the 18 standards used to declare performance was found to cost upwards of NOK 8000 (around EUR 800) combined, making a full assessment of the product's properties a costly affair as well as a time-consuming one.

It was also found that technical approval of products is well established in the Norwegian market and generally trusted by all the enquired actors. While the certification process is voluntary to participate in, project owners often require that only materials with a technical approval may be used in projects. As such, certification may be regarded as a requirement for a product to be competitive on the market.

In the interview phase, however, some respondents noted that technical approval alone is no guarantee against defects, as operating conditions in certain locations may still exceed product's certified performance limits. We noted a general tendency among contractors to only consider the stamp of technical approval when using a product, without necessarily considering its suitability for the project in question. Given two products with a technical approval, the less expensive one tended to be chosen regardless of capabilities.

4.5. Building Design Guides

The investigation into the building design guides found a level of detail and complexity too great to be easily manageable, causing a risk of some advice or recommendations being missed or for other reasons not followed. The nine building design guides were found to contain 322 paragraphs with a total of 977 individual recommendations. The design guides cross-reference each other, with the nine investigated guides referencing 22 other guides, presumably each containing around 100 more recommendations for the designer to consider. Additionally, as new guides are created or updated continuously, older guides are intended to be updated with new cross-references. However, there is a significant delay in this process. Both design guides that explicitly concerned vegetation on roofs were published too recently to be referenced in any of the other guides, which did not consider vegetated roofs at all.

On a detail level, the design guides explicitly consider technical risks. Technical risks were mentioned in a majority of the paragraphs. However, as stated by [64–66], information overload is a challenge involved wherever large amounts of information needs to be processed. The level of detail and amount of individual recommendations in the Building Design Guides makes it challenging to determine a hierarchy of risks and prioritize which aspects of the design to give the greatest level of attention. On a detail level, the recommendations give important advice, but a procedure for assessing the big picture appears to be missing. Risks and recommendations are sorted by topic and presented seemingly with equal importance, making it difficult to assess which challenges to give the highest priority in a situation with finite time and resources. While a skilled and experienced engineer can possibly manage this process, it is dependent on the experience of the individual designers and as such vulnerable to human error.

4.6. Project Delivery Methods

Because different project delivery methods organize the building process differently, each system allocates risks differently, and, therefore, the project delivery method should allocate the risk to the party with the greatest ability to understand it [67]. Consequently, the project delivery method will have a significant influence on how contractors perceive risks associated with blue-green roofs. In fact, the project delivery method is a variable affecting all actors as it determines, amongst others:

- The entry-point of the agent(s) (i.e., contractor participating in the design).
- The level of influence of the agent(s) (i.e., the contractor is responsible for the delivery).
- The level of integration (i.e., the use of a single project team to deliver both design and construction).

As seen, the introduction of concepts such as blue-green roofs make buildings more complex and, according to our interviewees, makes the building more prone to design flaws and construction errors [61]. A promising response to the challenges is the use of a collaborative project delivery method that seeks to align the client's interest with those of the supply chain [62]. For the contractor, collaborative project delivery proposes opportunities to reduce their quality risk (financial risk) as they are involved in an earlier stage and are given the opportunity to collaborate closely with designers and the project owner [42,46]. Choosing the right project delivery method is, thus, important for the management of quality risk. A method that involves the contractor (and possibly sub-contractors and suppliers) in the design will provide a platform from which the contractor can contribute with their expertise in constructability.

5. Discussion

5.1. How Do the Various Actors in the Building Process Perceive the Quality Risks of Blue-Green Roofs?

As summarized in Table 1, each of the investigated actors own quality risk in a different way, but the general idea seems to be shared in common: "If a defect occurs, it should not be our fault". For actors on the delivery side of the construction process, it is highly important not to deliver a faulty piece of work that leads to a defect. For the project owner, it is important to receive a building without defects.

The public property owners interviewed in the first phase of the research highlighted the importance of a professional organization on the ownership side. Large property owners may have cooperation contracts with specific contractors and designers, which acts as a measure against fraudulent workmanship. It is also considered important for the owner to be present for quality control and inspection on the construction site.

There is a high level of trust between actors in the Norwegian construction industry [68]. During interviews, property owners expressed trust in the contractors to choose proper materials and solutions. This was also seen in the investigated design–build tenders, where most project owners gave contractors great freedom in selecting a design for the green roofs. The project owners express a general trust in the contractor to deliver a working product. The reason may be that the owners in smaller organizations do not have the necessary competence and resources to create detailed specifications. The chosen delivery model may greatly affect the responsibility and the influence the owner may have on quality control.

On the delivery side of the project organization, a primary concern common to all involved actors is to avoid the responsibility of eventual defects. Designers choose solutions based on design recommendations and reports by advisory bodies. A designer must not recommend a solution without knowing that it will work, with references to the proper documentation. Likewise, suppliers use standards and technical approvals to ensure that the performance limits of their materials are well documented. In theory, if all actors ensure they are not doing anything wrong, building defects ought not to happen. However, the means by which risk is managed by each actor do not necessarily overlap. In cases where the ownership of responsibility is unclear, risks may be ignored and cause defects to occur. An example in the case of blue-green roofs could be the uncertainty of whose responsibility it is to ensure the roof is cleared of all debris before installation of the blue-green layers begins.

5.2. How Are the Risks Associated with Blue-Green Roofs Currently Managed?

For project owners, the level of risk management appears to depend on the capabilities of the owner of the project in question, and the chosen project delivery model. Large building owners may have good relationships with trusted partners, employ technical experts to follow up the project, and inspect the construction site on a regular basis. These resources are not always available to every building owner, in which case the owner appears to place a great amount of trust in the contractors. Smaller actors were found to select design–build contracts more often, wherein the contractor is responsible for both design and construction of the building. However, this approach gives the owner less influence over the building and may affect risk management.

Designers anchor the solutions they recommend for the project by referring to general recommendations issued by building research organizations. In Norway, the SINTEF Building Design Guides are vital in this regard by containing recommendations on a detail level. However, an assessment of the building design guides reveals a level of complexity that makes it challenging to see the overall picture and form a hierarchy of risks. In a sense, "the forest is lost among the trees." Making good use of the design guides in a practical situation requires a certain level of skill of the individual engineer.

Additionally, the building design guides do not cover every building detail or design feature. As an example, blue-green roofs are a novel building element not yet fully treated in the design guides. There is a guide for extensive sedum roofs, but there are challenges of blue-green roofs that it does not cover. For instance, the substrate layers of a blue-green roof will be thicker and have a greater capacity to hold water than an ordinary Sedum roof, which allows weeds to grow more easily. Maintenance plans based solely on recommendations for Sedum roofs may not cover this issue or other special cases. The engineers involved in the project will have to find their own solutions to such challenges. Thus, the risk management may rest entirely on the experience and expertise of individuals, which may not always be sufficient to meet the needs of every case. The sheer number of individual recommendations in the design guides also makes it challenging to use them to follow up work on the construction site. Third-party control of building physics solutions is required in construction projects in Norway, which serves to both reduce and share the risk for the designer.

Material suppliers manage quality risk by determining and documenting the usage and performance limits of their materials. In theory, this ensures that the suitability of a material for an individual application can be determined accurately. However, this approach to risk management does not necessarily prevent misuse of the material. Like with the building design guides mentioned above, the amount of information presents a level of complexity that may not be manageable in practice. While a skilled engineer working closely with a product could know the details of testing standards to know where and how to apply the product correctly, this information may not necessarily be available to the responsible person in the construction project. The required expertise exists somewhere, but one cannot assume everyone to be an expert. This sentiment echoes that of Josephson and Hammarlund [35], who found lack of knowledge to be one of the largest causes of defects in investigated construction projects.

5.3. How Can the Management of Quality Risk Be Improved?

The relevant quality risks in a project containing a blue-green roof exist within a manifold of partially overlapping perspectives and responsibilities, and the term carries different meanings to different actors, as shown in Table 1. The inherent complexity of the construction process means no single actor can take steps that reduce quality risks for everybody. Rather than suggesting measures for each involved actor, four different approaches to addressing quality risk management have been identified by the authors: (i) improvement of rules and regulations, (ii) improvement of competence, (iii) improvement of process flow, and (iv) improvement of best-practice design guidelines. Below, the merits and disadvantages of each strategy are outlined.

Rules and regulations vary between countries and sometimes even regions. In Norway, the regulations are function-based, which gives designers great freedom and leaves room for creativity and cross-disciplinary cooperation to test new solutions. The regulations already state that moisture damages must not happen [20], but leaves it up to the individual designers to find ways to achieve this. Further regulatory measures are likely to restrict the designer's freedom and may not fit within this style of regulatory framework. However, it could be possible to strengthen the requirements of documenting compliance with the regulations.

As demonstrated, competence and awareness of the main challenges are key to managing the risks of blue-green roofs. Several existing risk management strategies hinge on the competence of individuals. The required expertise to solve a problem may be found somewhere in the project organization, or somewhere in the documentation. However, not all project organizations are large enough to contain all the required expertise, and this research shows that documentation alone may not provide the right information in an understandable fashion to a non-expert. The choice of delivery model to include better cooperation and sharing of knowledge may overcome these limitations to a certain degree.

A multi-disciplinary guideline to guide the process of acquiring blue-green roofs may be helpful as it could signal how to overcome challenges, set up design priorities, and allocate responsibility on a general basis instead of going deeply into the technical specifics. As an example, a report concerning the procurement process of expertise for the design and construction of climate adapted buildings illustrates how such a guideline could appear in practice [69]. The guideline would need to consider a manageable number of focus points to be practically useful to all involved actors.

For best-practice design guides, this article illustrates how they are considered helpful, but the volume of information is difficult to manage, and adding more recommendations might yield diminishing returns. It is evident that a structuring of the recommendations might be more useful than solely making more recommendations. A motivating example of this structuring was carried out by Asphaug et al. [70], who assessed the design recommendations for habitable basements in the SINTEF Design Guides and extracted 10 key challenges around which the recommendations were grouped. Creating such a hierarchy by allocating the hundreds of individual recommendations to a manageable number of main challenges makes it easier to assess risks in a systematic fashion.

6. Conclusions

The research shows that the different actors in a construction project perceive and manage quality risks differently. Each actor generally has a means to manage quality risk in their own part of the process, which in theory creates an overlapping patchwork of risk management that in sum will cover the entire project. However, there are gaps between the various risk management strategies, usually where the responsibility of one actor ends and that of another begins. Notably, it is shown that documentation meant to avoid risks will either be insufficient to cover every detail, or too complex to be put to practical use in every project. A significant level of expertise is required to create a whole picture from the many details presented in the best-practice design guidelines and to understand how to adapt and apply them in special cases. This makes them insufficient as a sole tool for risk management. Likewise, the technical approvals of construction products may not necessarily suffice to assess their suitability in a given project, because the details of their performance limits are not easily understandable to the procurement agent of the project. Project owners may subvert the need for detailed expertise in the building process by selecting contract forms that place the responsibility for design and construction on a single contractor; however, they will still end up carrying the risks of defects in the long term.

It follows that a framework to reduce the total quality risk in a building project cannot focus solely on one actor or one phase of the process, but it needs to consider multiple perspectives and project phases. It also needs to address the issue of thoroughness versus complexity, hitting a balance of covering enough issues without being too voluminous to be practical and understandable to those who use it—which is to say, anyone in the building process.

Future work will attempt to analyse the quality risks associated with blue-green roofs in a systematic fashion and present a framework for risk management from multiple perspectives. An analysis of the situation of quality risk for blue-green roofs in other countries could also be conducted. The overall goal will be to reduce the overall quality risk associated with blue-green roofs, delivering a reliable means of stormwater management without compromising the integrity of the building.

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Paper 4

Erlend Andenæs, Berit Time, Tore Kvande & Jardar Lohne

Surpassing the Limits to Human Cognition? On the Level of Detail in the Norwegian Building Design Guides

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Paper 4

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Surpassing the Limits to Human Cognition? On the Level of Detail in the Norwegian Building Design Guides

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Abstract: The SINTEF Building Research Design Guides are a series of Norwegian building technical recommendations. The design guides are highly reputed and widely used in the Norwegian construction sector, serving as a link between the technical regulations and the design process of the individual construction project. This paper examines the element of risk in the use of multiple design guides to extract information about a topic not explicitly covered by any single guide, using the example of blue-green roofs. The research has been conducted in the form of a document study. While the advice given in the design guides is both valid and coherent, the amount of information presented is likely to be overwhelming for industry professionals. There are great degrees of awareness of quality risk present in the individual design guides, but an overall risk picture is not presented. Input from the fields of project management and psychology can help develop risk awareness strategies. The design guides may benefit from an aggregate level of information, where main technical challenges are grouped into super-level categories.

Key words: Risk, quality risk, blue-green roofs, human cognition.

1. Introduction

In Norway, the requirements of the building code are given on a function-based level [1]. The technical regulations for buildings (TEK17 [2]) specify requirements of the Planning and Building Act of 2008. Any technical solution may be chosen as long as it complies with these requirements. The Norwegian Building Authority [3] expresses the structure of the legislation as follows:

"*The collected requirements of the government, defined in the Planning and Building Act and its associated regulations, set a minimum level of quality and safety to be fulfilled by the finished building. TEK10 [The Technical Regulations of 2010] specifies requirements on all essential topics pertaining to health, safety, environment, and usability. The requirements are stated in the form of overall, qualitative, functional requirements*" (our translation).

Note that the functional structure and role of the current regulations (TEK17) are identical to that of TEK10 [4]. This form of legislation gives architects and designers wide freedom, but there is also an inherent risk in that this large degree of freedom left to designers entails a potential high level of quality risk—preliminarily defined here as *the probability and consequences of technical building defects*. The core of the issue is to ensure that the chosen solution will remain functional throughout its intended life span.

Challenges of quality risk in the built environment today can be exemplified through the introduction of so-called blue-green roofs [5]. One challenge brought by climate change in the Nordic region is an increase of the number and intensity of precipitation events [6]. Heavy rainfall may exceed the capacity of urban stormwater drainage systems, necessitating local measurements to retain and detain stormwater. Blue-green roofs, wherein vegetated roof assemblies

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are used to store water on rooftops, constitute such a measure. While these roof structures intend to reduce the risk of flooding, they introduce a novel state of operation for the roof as part of a building envelope.

The main quality risk element induced by blue-green roofs is the risk of water intrusion into the building. This may occur due to design flaws, build flaws, material flaws, accidental damage or degradation over time [7]. One particular challenge within a Norwegian climate is the prevalence of freeze-thaw cycles. It is known from experience in the Norwegian building sector that roof damages are common, although comprehensive building statistics are not available [8]. Research on the limited datasets available shows that intrusion of precipitation water is the culprit in around 2/3 of all roof defect cases [9], and that moisture in some form is involved in ¾ of all building defect cases [10]. It has also been noted [11, 12] that vast resources are spent in the construction sector to repair defects, before and after handover. Defects constitute a recurring problem in the construction sector, which is likely never to be fully eliminated due to the inherent complexities of construction projects. Analyses of quality risk may serve a crucial role in *lowering* the number of defects, even if eliminating them is likely impossible.

In the Norwegian building sector, the main strategy for mastering quality risk is to follow the prescriptions of the SINTEF Building Research Design Guides, hereafter mainly referred to as "design guides". The SINTEF Building Research Design Guides (Norwegian: Byggforskserien) are an authoritative series of multidisciplinary building technical recommendations published by SINTEF Community (formerly SINTEF Byggforsk) which is widely used in the Norwegian building sector. The principal objective of the design guides is to adapt experience and results from practice and research to be of practical benefit to the construction industry [13]. The design guides serve as a link between the technical regulations and the design process of the individual construction project, by presenting pre-accepted solutions that comply with regulations as well as best practice from a building physics standpoint. Through understanding the SINTEF Building Research Design Guides, one may understand, for instance, the risks of blue-green roofs in a Norwegian climate. The design guides provide a comprehensive list of individual risk elements. However, the practical application of the design guides involves an element of risk considering the total understanding of the subject by the user. The level of detail is, in fact, impressive, yet no immediate overall picture stands out.

To assess this general problem, the following research questions have been investigated:

- How does risk management factor in the structure of the SINTEF Building Research Design Guides?
- What challenges exist related to the structure of the design guides?
- How can the quality risk management in multidisciplinary design guides be improved?

The following limitations apply to the research: a limited selection of design guides, those relevant to blue-green roofs, is examined—a full list is provided in Table 1. The validity of the individual recommendations in the design guides is not evaluated. It has not been evaluated whether there are contradictions in the material, nor are overlaps accounted for (certain recommendations are repeated in several of the evaluated design guides). The recommendations are not weighted according to importance or relevance.

2. Theoretical Framework

2.1 Approaches to Quality Risk

While risk analysis literature is comprehensive with many well-established and refined methods of quantifying risk, the theory has seen little application on the risks of building defects. In a series of articles, Aljassmi et al. [14-16] apply risk analysis methods on building defects. The articles analyze the magnitude and pathogenicity (ability to trigger other risky conditions) of a set of identified defect causes. Similarly, Nieto-Morote and Ruz-Vila [17] analyzed construction defects using a fuzzy method approach. While there are some drawbacks for restricting calculations to known and specified defect causes, it would not be practically feasible to do calculations on unknown factors. In itself, this exposes an inherent challenge in risk management: there will, in general, be unknown factors that cannot be analyzed in advance, but which will influence the project outcome regardless. Building projects are inherently complex, and will involve complex causal relations that cannot be quantified in a practical fashion, such as human factors in design and assembly, post-construction modifications to the building, the impact of aging, adherence to use and maintenance plans, etc. As such, there are inevitable limits to quantify risk [17]. Understanding the full spectrum of risk encountered in building projects, broader perspectives need being taken into account.

While the SINTEF Building Research Design Guides are primarily relevant for the Norwegian building sector, similar guidelines exist in different countries worldwide. They are not however, to the knowledge of the authors, made to the level of detail found in Norway. In Denmark, the independent organization BYG-ERFA develops and publishes design guides with a similar scope and purpose to those in Norway [18]. In Sweden, the Moisture Research Centre (FuktCentrum) at Lund University and The Research Institute of Sweden (RI.SE) perform research and publish guidelines for moisture safety in building projects [19]. The Finnish Rakennustieto (RTS, Building Information Foundation) conducts research and publishes guidelines for the construction industry in Finland, with offices in Russia and Estonia [20]. In other countries, national building authorities may in some cases also issue guidelines (e.g. Ref. [21]). Some examples have been collected by Asphaug et al. [22] who mentions Canada and the US in addition to the aforementioned countries.

2.2 Quality Risk Perspectives

Little research seems to have been carried out on the level of risk of defects of building envelopes. In project management literature, the term “uncertainty” is usually favoured over “risk” as it covers both positive and negative outcomes. The term is defined as “An event that, if it occurs, has a positive or negative effect on a project’s objectives” [23, 24]. Strategies to manage risk (negative outcomes of uncertainty) include avoiding, reducing, sharing or accepting the risk [25]. Note that the perspective of risk depends on one’s involvement and role in the project, this would also affect the approach used towards risk management [26].

Risk, or uncertainty, is actively evaluated and managed in many aspects of the construction sector. However, most risk management literature appears to focus on process risks, related to the effectiveness and efficiency of the construction process itself, or on the economy of the individual parties [27]. The quality of the building is seldom focused on in a risk perspective, but rather treated as a separate field of study [28].

The term “quality risk” is not well defined in literature. Other terms found to describe the same subject include “defect risk” [29, 30], “quality management” [28], “quality deviations” [31] or “defect management” [16]. In the following, we use “quality risk” to include all of these terms. Identified defect categories include design flaws, build flaws, material flaws, accidental damage, gradual degradation, and use flaws. The latter two categories of defects occur during the use phase of the building (barring exceptionally long construction periods) and are excluded from the scope of this article.

It should be noted that while “quality risks” and “building defects” may appear to be synonymous terms, this is not the case. Building defects are an outcome of quality risks. The term “quality risk” expresses a potentiality, while “building defects” expresses an actuality.

Experiences from the Norwegian construction sector suggest that the current practice of quality risk management in the design process does not work satisfactory. Even though correct design and construction of roofs is fundamentally known information, defects still occur [9].

Quality risks can be encountered in many stages of the building process [32]. It is found necessary to limit the scope of this article to only include parts of the process, namely the design stage. This article will aim to investigate how the SINTEF Building Research Design Guides determine risk management using the case of blue-green roofs. Blue-green roofs are a novel building element that is not explicitly covered by a dedicated design guide, but whose principles of construction can be extracted from a handful of existing design guides. Seen in isolation, the design guides serve as a measure to reduce quality risk. However, it is conjectured that aspects of their implementation might carry an inherent risk that hitherto has received little attention. The challenges to their use are varied, and exist on at least three levels:

(1) The process of extracting relevant knowledge from the sum of several design guides is complex, and there is no super-level guidance to aid it.

(2) The challenges involved in blue-green roofs as described in the design guides exist over the full timeline of the building’s life span, from conception to the use phase.

(3) Blue-green roofs are erected in the concurrence between several crafts and disciplines, involving challenges related to water management, structural mechanics, thermal insulation, landscape architecture, waterproofing, and several others.

2.3 Building Defects

Limited research has been identified concerning the extent of building defects in Norway. A study by Ingvaldsen [33] in the early 1990s estimated that approximately 10% of the entire production of the Norwegian building sector concerned the repair of defects, either before or after the moment of handover. In total 60% of the defects were found to originate in choices made before the construction. Further research in 2006 estimated that the repair of process-related defects constituted 2-6% of the annual net production value of the building sector [12]. Newer, comprehensive data are not available. Organizations such as SINTEF or certain insurance companies register and keep track of defects on building projects they have been directly involved with, and studies have been conducted on these limited data sets [9, 10, 34, 35], but no shared platform exists to create a comprehensive set of data on a national level. A project started in 1998 aimed to create a national database of building defects [8], but such a database has yet to materialise.

Qualitative interviews in recent years indicate that defects on roofs are still a challenge in the Norwegian building sector [7]. Comprehensive numbers are not available, but there is little reason to believe the situation has improved since the 1990s. A white paper from 2012 concludes a general lack of information on the quality of the building stock in Norway [36]. Given the changing climate with an increasing amount of precipitation [6], the risk of building defects is increasing.

2.4 Norwegian Legislation

The general structure of the Norwegian building regulations is described by Skatland et al. [1], Lisø et al. [13] and Stenstad [37]. It is illustrated in Fig. 1. The legislation is structured hierarchically with the Norwegian Planning and Building Act at the base, specifying overall objectives of the building code. Functional requirements are quantified in the technical regulations, TEK17. The text of TEK17 is also accompanied by a guideline addendum (VTEK) for every paragraph, which serves to contextualize the requirements of the regulations and present pre-accepted solutions. VTEK frequently refers to the SINTEF Building Research Design Guides for practical examples, documented solutions, and further information about the subject of the regulations. Operative requirements are given in Norwegian and European standards. The SINTEF Building Research Design Guides are found at the bottom of the hierarchy, describing documented solutions based on all the above requirements. Note that independent evaluation and verification of the chosen solutions are required alongside the Building Design Guides. Third-party control might also be required to validate designs in certain fields such as structural engineering, fire safety, and building physics, depending on the type of building.

Several illustrations of the formal framework governing Norwegian building regulations exist. Given the complexity of the system, these different representations differ according to the perspectives they want to accentuate. Probably the best is found in Ref. [13], since it places the guidelines clearly in relation to the SINTEF Building Research Design Guides. Among other representations, see also Ref. [1].

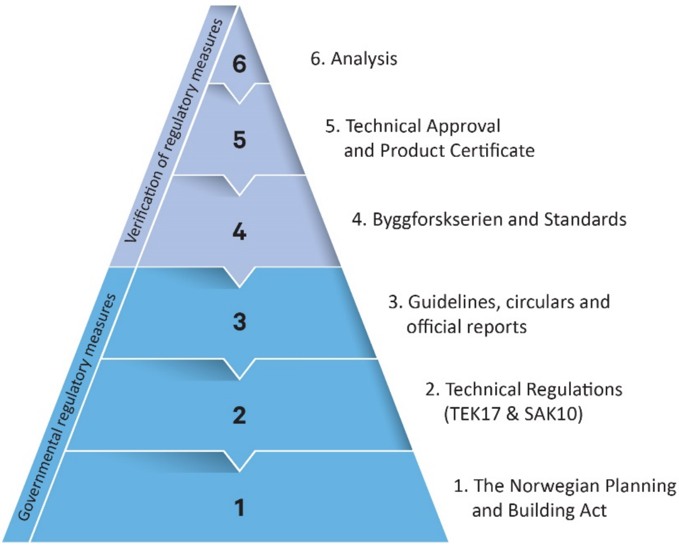

Fig. 1 The hierarchical structure of the Norwegian building regulations.
Source: adapted from Ref. [13]. Used with permission.

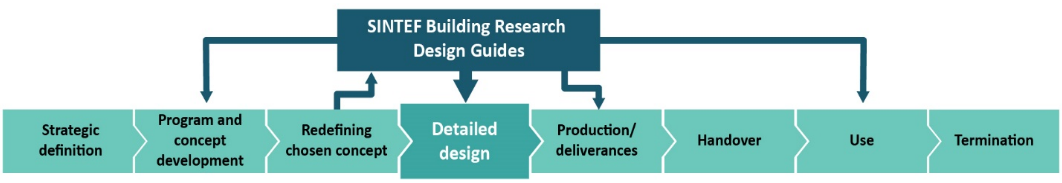

Fig. 2 The role of the SINTEF Building Research Design Guides in the construction process. The design guides aid planning, design details and facility management. Solutions chosen in the concept phase affect which design guides are consulted in the design, construction, and use phases.
Source: phase model adapted from Ref. [38].

2.5 The Role of SINTEF Building Research Design Guides

The Norwegian Building Research Institute (NBI) was founded in 1953, after a recommendation from a committee appointed by the Norwegian Association of Science and Technology (NTNF). Prior to this, some building research had been conducted at the Norwegian Technical College (NTH) since the early 1920s, but early building research in Norway was scattered and poorly organized [39]. The main goals of NBI were to conduct and coordinate building research and translate its results into useful practical solutions.

The first building design guides were published in 1958, in the form of "guide sheets". Handbooks in building design were published prior to this, but in practical use they were replaced by the design guides. Each building design guide covers an aspect of a building construction; examples include "walls against terrain", "additives to concrete mixes", "safety windows" or "securing water pipes against frost". SINTEF also issues Building Research Guides not directly related to building design, with a series for construction planning and one for building management. These series are outside the scope of this article.

The design guides supplement the construction process as shown in Fig. 2. They are most commonly used as a tool for detail design of individual building elements, but also advise on the concept development, construction process as well as the maintenance, operation and management (MOM) phase.

The guide text (VTEK) to the Norwegian technical regulations for buildings (TEK17) frequently refers to the SINTEF Building Research Design Guides for solutions that meet the requirements or to give more information on relevant topics. In perhaps the most explicit example, the introductory paragraphs to TEK17 state:

Norwegian Standards and design guides from SINTEF's Building Research Design Guides are useful tools to create good buildings. Therefore, we have added links to certain standards and design guides below the individual paragraphs, even though these tools are not available for free (in Norwegian).

Additionally, the guide text to paragraph 2-3 explicitly references the SINTEF Building Research Design Guides:

It shall be documented that the designed solutions and product specifications comply with the specified performance (in Norwegian).

Pre-approved solutions include solutions that are certified or otherwise approved, solutions specified in the SINTEF Building Research Design Guides, or other reputable sources (in Norwegian).

2.6 The "Chain of Recommendations"—What Are Designs Based on?

When creating detail plans for buildings, designers rely on external documentation to determine which solutions to recommend to the architect. It is the responsibility of the designer to ensure that the recommended solutions are sound and meet the technical requirements. This is ensured by grounding the recommendations in documented solutions and declarations of performance, i.e. technical reports, product datasheets, and officially issued recommendations. The SINTEF Building Research Design Guides present an example of the latter; containing pre-accepted solutions that meet the requirements of the technical guidelines. The design guides are not legally binding, but they are considered a useful tool and reference source for designers. A technical verification from the individual designer is still necessary to determine the suitability of the solutions presented in the design guides for the project in question [1, 37].

2.7 Cognitive Perspective of Apprehension—Mastering Complexity

Information overload is a recurring problem whenever humans need to process large amounts of information [40]. The problem has been recognised and examined in fields such as, among others, social studies [41], public relations [42], business and marketing [43], and the offshore industry [44]. In a complex task such as designing a building, being overwhelmed by information and requirements may increase the difficulty of the task and increase the risk of error.

An issue highlighted by Tang et al. [45] is that of data, information, and knowledge. In their article, the nature of data is “a statement taken at face value”, information is “interpreted data that informs”, and knowledge is “facts, feelings and truths hat make up what is known”. Knowledge can both be explicit (recorded), implicit (gleaned from recorded information) or tacit (existing only in the mind). The process of gaining knowledge from data, or even from information, is not automatic or necessarily easy. When the volume of information becomes too big, the process of making proper use of it itself becomes a daunting task. A form of structuring or visual presentation of the information volume could be a helpful tool to sort through large amounts of information [40].

While no figure could be found for the mental capacity of the human brain, for the experimental test used in the research by Falschlunger et al. [40], 180 data points were considered a “high” amount of information for a person to process. The “medium” level is set at 120 data points, which is approximately the average amount of information contained in each of the examined Building Design Guides.

2.8 Case: Blue-Green Roofs

The importance of solid recommendations can be highlighted through an example of a novel building element being introduced to the industry. A changing climate bringing increased precipitation in Norway causes a need for local stormwater management, of which blue-green roofs constitute a popular solution. However, there is a dearth of recommendations for and experience with blue-green roofs in the Norwegian building industry. Some guidance can be found in the existing design guides for compact roofs. Using multiple design guides to find information about a novel building element accentuates the challenges inherent in the structure of the design guides.

Blue-green roofs are roof assemblies wherein a mat of vegetation and its substrate layers are used to store precipitation water, making the roof part of a stormwater management strategy. Any green roof built for this purpose can be considered a blue-green roof [46]. Another definition separates green roofs, which only provide detention (temporary storage) of water and blue-green roofs, which provide retention (water loss through evaporation) as well [5]. In Norway, climate change is expected to cause an increasing frequency of extreme precipitation events [6], which may lead to flooding in urban areas. Using roofs to manage stormwater is an important part of the strategy to combat urban flooding [47]. Different types of blue-green roofs are illustrated in Fig. 3. All the types shown here are built as flat roofs with a compact structure.

However, the addition of vegetation to a conventional compact roof will impact its operating conditions, most notably by covering the waterproofing layer. This decreases the likelihood of leaks being detected before they have had significant time to damage the building. Additionally, repairing a blue-green roof is more expensive than a conventional roof as the vegetation and substrate must be removed from the roof during the repair process. However, as the roofing membrane is buried under the blue-green layers, it gets a significant degree of protection from the elements and traffic on the roof [48].

It follows that it is imperative to manage risk elements that could impact the building’s quality in the design and construction phase. Such risk elements include design flaws, build flaws, use of inadequate

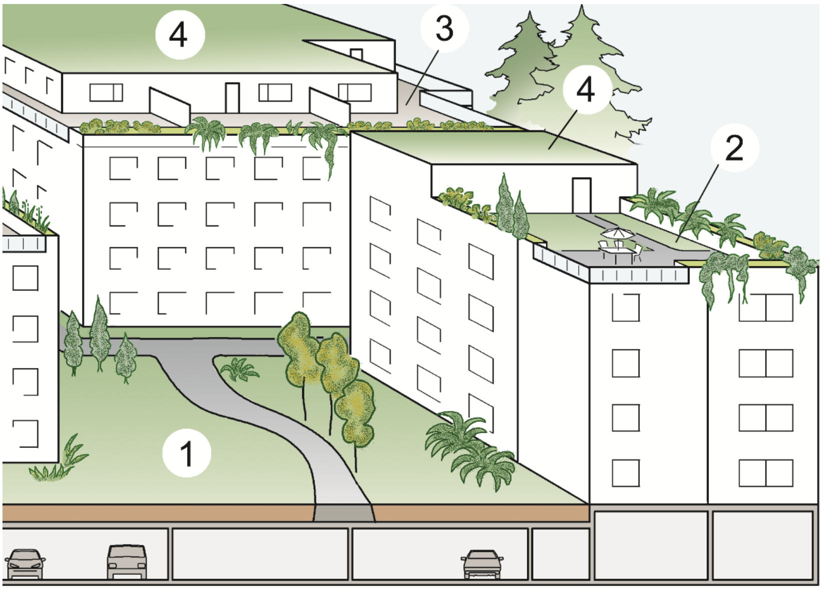

Fig. 3 Green and blue-green roofs in a typical residential construction project: (1) intensive green roof, park, built for vehicle access; (2) roof terrace with lawns and flowerbeds; (3) roof terrace with permeable paving, a "blue-grey roof"; (4) lightweight, extensive Sedum roof.
Illustration: SINTEF/Klima 2050.

materials, or accidental damage. Quality risk should be approached with the same rigidity as other forms of risk in the building sector, i.e. the risks of delays, cost overruns or personal injury, which have traditionally received the greatest focus in risk management literature [27].

The Norwegian climate poses specific challenges to the construction of flat roofs in general, and blue-green roofs in particular. The most important of these is frequent freeze-thaw cycles, changing climate conditions over the year, strong winds, and heavy precipitation [46]. The challenging climate has heavily focused the development of climate robust solutions within the SINTEF Building Research Design Guides. In addition, previsible climate changes will pose new and hitherto hardly known challenges to the built environment in general and the roofs of buildings in particular. The most important of these seems to be a dramatic increase in heavy precipitation and temperature increases [6].

2.9 Knowledge Gap

Taking all the above into account, a knowledge gap becomes apparent. Designers use the building design guides as a tool to anchor their design recommendations, but how can the guides be applied to reduce risk for a novel building element not directly addressed by any individual guide? It therefore is necessary to examine the application of multiple design guides with regards to quality risk, in the case of this article by using blue-green roofs as a case study.

3. Method

3.1 Desktop Study

A desktop study was conducted, with a twofold purpose: firstly, to assess the amount of information a user of the SINTEF Building Research Design Guides would need to process; secondly, to map the level of risk management made explicitly and implicitly in the design guides. A selection of design guides was chosen and analysed paragraph by paragraph. All individual recommendations in the body text of the assessed design guides were counted and sorted. Mentions of the concepts of risk in the text were also counted.

3.2 Selection Process

Design guides directly pertaining to compact roofs and green roofs were examined. This includes design guides from Sections 525.2, 525.3 and 544; a full list is given in Table 1. These guidelines were chosen to match a hypothetical roof construction project like that shown in Fig. 3, where a designer would use a variety of design guides as a reference to design the various roofs of a building. The focus on roofs in this article was chosen to make use of previous research on compact roofs, a so-called "convenience selection" according to Krippendorff [58]. Hereafter, the individual examined design guides will only be referred to by number.

3.3 Content Analysis

The text of the selected design guides was analysed paragraph by paragraph. Examined paragraphs include

Table 1 List of examined design guides.

Number	Year of publication	Norwegian title	Translation of title	Length [words]	Reference
525.207	2018	Kompakte tak	Compact roofs	4,900	Ref. [49]
525.304	2007	Terrasse på etasjeskiller av betong for lett eller moderat trafikk	Terrace on concrete floorplates for light or moderate traffic	3,900	Ref. [50]
525.306	2009	Terrasser med beplantning på bærende betongdekker	Terraces with vegetation on load-bearing floorplates	3,600	Ref. [51]
525.307	1999	Tak for biltrafikk og parkering	Roofs for car traffic and parking	4,350	Ref. [52]
544.202	2011	Takfolie – egenskaper og tekking	Roofing membranes—properties and installation	5,100	Ref. [53]
544.203	2011	Asfalttakbelegg - egenskaper og tekking	Asphalt sheet roofing—properties and installation	5,300	Ref. [54]
544.204	2008	Tekking med asfalttakbelegg eller takfolie – Detaljløsninger	Roof installation with asphalt sheet roofing or roofing membranes—detail solutions	2,750	Ref. [55]
544.206	2016	Mekanisk innfesting av asfalttakbelegg og takfolie på skrå og flate tak	Attachment of asphalt roofing and roofing membranes on sloped and flat roofs	5,150	Ref. [56]
544.823	2013	Sedumtak	Sedum roofs	4,450	Ref. [57]

Note that a newer version of guide 525.307 was published while this article was in writing.

Table 2 Modality level of recommendations in the SINTEF Building Research Design Guides.

Modality level	1	2	3	4
Example wordings (Norwegian)	• Can • May • (Kan)	• Should • "SINTEF recommends…" • "It is recommended that…" • Statements in imperative • (Bør)	• Must • "It is important that…" • "… is necessary" • (Må)	• Required • References to legislation • (Skal)
Meaning	An option	Recommendation	Strong recommendation	Required by legislation

Table 3 Use of concepts concerning risk and the definitions used to categorize these.

None	Implicit	Explicit	Formalized
Paragraph does not concern moments of risk.	Paragraph concerns moments of risk but does not specify how they may occur, or their consequences.	Paragraph mentions concrete consequences that are to be avoided.	Measures to mitigate risk are directly specified or quantified.

only the main body of the design guide, and not the sections at the beginning and end, which concern the scope of the design guide, references to legislation, product standards, and further reading. Text in figures was also excluded from the analysis.

The validity or technical accuracy of the recommendations in the text was not assessed, but the modality of individual recommendations was counted by the criteria presented in Table 2. The four levels of modality were defined according to SINTEF's writing guidelines for the Building Research Design Guides [59]. Each paragraph of text could include several individual recommendations.

Table 3 shows the criteria for determining the overall risk modality of each individual paragraph. Not every recommendation given in the text contained a mention of risk, and not every mention of risk could be tied to a specific recommendation, hence it was decided to count the risk modality according to the paragraph and not according to the individual recommendation.

4. Results

4.1 Extent of the Content

The nine examined design guides contained 337 paragraphs of recommendations that were examined in depth. This number excludes, for instance, paragraphs explaining the scope of the design guides, background information, figures, information about the authors, and references to further reading. The examined paragraphs contained 977 specific recommendations in total. Thus, each design guide contains a little more than 100 specific recommendations on average.

The examined design guides also contained references to other design guides for supplementary information. The references are listed in Table 4. It follows that an engineer seeking a broad overview of the supplementary information would have to read through 22 additional design guides, containing an estimated 2,200 individual recommendations to keep track of. Also note that cross-references within the examined design guides do not cover all the nine guides, as two of them were created after the latest revisions to any of the other relevant guides. While the remaining two guides could easily be found using SINTEF's Building Research Design Guide website, their existence cannot be surmised from the text of the remaining design guides.

4.2 Modality

The modality of the recommendations in the nine examined Building Design Guides is distributed as shown in Fig. 4. It is shown that modality level 3 (strong recommendation) is the most commonly given, followed closely by level 2 (recommendation). Regulations (modality level 4) are listed comparatively rarely in the main text of the design guides. Given the role of the design guides as a tool for interpreting the regulations and suggesting a best practice based within their framework, this distribution is not surprising.

Table 4 SINTEF Building Research Design Guides examined in this document (left) and other guides referenced in their text (right). Guides in brackets in the right column are references between the examined guides. Note that none of the other guides reference guides 525.306 or 544.823, as these were written after the latest revision of the other guides.

Examined design guides	Referenced design guides		
• 525.207	• 470.103	• 525.101	• (544.202)
• 525.304	• 470.112	• (525.207)	• (544.203)
• 525.306	• 471.043	• (525.304)	• (544.204)
• 525.307	• 471.044	• (525.307)	• (544.206)
• 544.202	• 514.114	• 525.861	• 544.803
• 544.203	• 520.339	• 525.886	• 571.803
• 544.204	• 520.415	• 525.931	• 573.121
• 544.206	• 523.621	• 525.933	• 700.802
• 544.823	• 523.731	• 527.245	• 725.118
	• 525.002	• 541.421	• 744.201

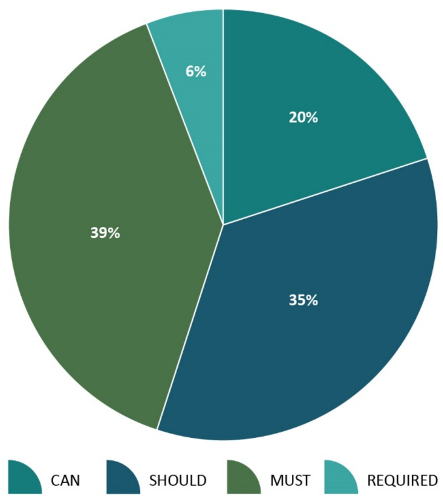

Fig. 4 Distribution of modality levels of the 977 individual recommendations given in the examined material.

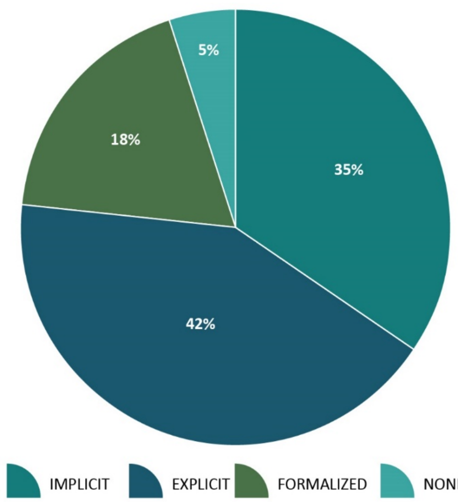

Fig. 5 Distribution of risk explicitivity levels among the 322 examined paragraphs, according to the definitions in Table 3.

4.3 Use of the Concepts of Risk

The distribution of risk awareness in the 322 examined paragraphs is shown in Fig. 5. It shows than almost two thirds of the paragraphs contained specific references to risks, with the majority of the rest implying a risk scenario without specifying it. Only less than 5% of the paragraphs had no references to risk at all.

5. Discussion

This paper aimed to answer the following three research questions: How risk management factors in the structure of the SINTEF Building Research Design Guides, what challenges exist related to that structure, and how risk management in multidisciplinary design guides can be improved.

5.1 How Does Risk Management Factor in the Structure of the SINTEF Building Research Design Guides?

The SINTEF Building Research Design Guides work as a measure to reduce quality risk on a detail level, by presenting documented solutions for a large variety of aspects of construction. However, according to Ingvaldsen [12], 60% of all building defects originate in choices made before the start of construction. This primarily includes the design phase, which is the phase receiving the most practical input from the design guides. A need for risk management through design guidelines is clear and evident. On a paragraph-by-paragraph level, the design guides display a high level of risk awareness. There appears to be a lack of focus on the overall risk picture. While each recommendation in itself might be a solid piece of advice with a clear risk perspective, assembling a greater understanding of risk in the overall building design is difficult. Research from the field of psychology suggests that the amount of information provided in the examined design guides may be too high for the human brain to process effectively, leading to a risk of recommendations not being followed. This is especially the case if multiple design guides are used concurrently.

5.2 What Challenges Exist Related to the Structure of the Design Guides?

It is shown that the amount of information conveyed to the reader within the selection of relevant design guides may be greater than what is humanly possible to process. Even though all the information required for a given design project may be contained within the Building Design Guides, they do not present a procedure by which the information can be used to reduce risk. While a skilled and experienced engineer can possibly manage this process, it is dependent on the experience of the individual designers and as such vulnerable to human error.

The hierarchical structure of the Norwegian building guides presupposes that an independent evaluation and verification is performed even if the Building Design Guides are used as a basis for the design process. No mechanism has been found that ensures the accuracy of this verification, although the adoption of third-party control at least intends to help reduce the risk appreciably.

5.3 How Can Risk Management in Multidisciplinary Design Guides Be Improved?

The fields of project management and finance have long since developed tools to manage risk and a culture for identifying and avoiding it. While some of the methods cannot readily be adopted for quality risk management, there still is much to learn from conventional risk management. In terms of suggestions for the building design guides, the authors have identified the following general principles that would aid risk management in their application:

- Stratification—presenting guidelines for how guidelines are used. For instance, a super-level tool or guide to aid the extraction of information from multiple design guides. Some risks are greater or more commonly encountered than others, and a solidly defined hierarchy can help determine which risks to give particular focus in the design process.
- Simplification and consolidation—creating a hierarchy of the main technical challenges related to the building part in question, by outlining the greater principles to be followed in addition to specific details. An example of such consolidation of information is seen by Asphaug et al. [22], who assessed the various SINTEF Building Research Design Guides relevant to habitable basements and identified 10 main challenges for moisture safety. Likewise, Sivertsen et al. [60] present a 21-point, multidisciplinary "check list" for procurement in climate adapted buildings. By this way, a large amount of detail information can be sorted and allocated into a manageable number of overarching concerns, which makes it easier to assess risk in a systematic fashion.
- Cooperation—using a cooperative project delivery model to take full advantage of the knowledge and experience of all participants in the project. As mentioned above, blue-green roofs are an example of a building part involving several disciplines and risk perspectives in concurrence, where no single actor has a complete overview of all risk elements. However, the required expertise is more likely to be found within the project organization. A delivery model that encourages cooperation makes it easier to identify, communicate, and manage these risks, particularly those that occur in the interface between disciplines.

6. Conclusion

Building design guides are a tool used in several countries to identify and assess building technical challenges. The study shows that the SINTEF Building Research Design Guides serve as a risk reduction measure on a detail level, a purpose they are widely used for in the Norwegian building sector. The majority of paragraphs in the examined material showed a high level of risk awareness. However, being written as a large number of narrow recommendations, a wider perspective tends to be missing from these design guides. The amount of information presented may also be greater than what a single person or project organization can process, increasing the risk of advice not being followed due to a slip of perception or of communication. The high number of continuously updated design guides also makes it difficult to stay up to date on the latest recommendations. While using the Building Design

Guides effectively to reduce risk may not be an insurmountable task, it depends largely on the abilities and experience of the individual designer. This implies there is a significant and largely unaddressed human factor in play when using the design guides as a tool for reducing quality risk.

While this research is limited to the Norwegian design guides, the same fundamental challenges are likely to be faced by multidisciplinary design guideline tools used in different countries. Future research should investigate and compare guidelines in multiple countries to assess how—and how successfully—these challenges are addressed internationally.

Data Availability Statement

Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request. This includes the spreadsheets used to count the recommendations in the design guides, but not the text of the design guides themselves.

Acknowledgements

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Paper 5

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Risk Reduction Framework for Blue-Green Roofs

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Paper 5

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Article

Risk Reduction Framework for Blue-Green Roofs

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Abstract: As climate change in the Nordic region brings an increase in extreme precipitation events, blue-green roofs have emerged as a solution for stormwater management, hereafter referred to as "blue-green roofs". The addition of blue-green layers on a conventional compact roof represents several multi-disciplinary technical challenges and quality risks that must be managed. This paper aims to list and address the key building technical challenges associated with blue-green roofs and to present a framework for managing these risks. Literature and document studies as well as qualitative interviews and expert meetings have been conducted to collect research data on defects in blue-green roofs and causes thereof. A list of nine key challenges has been extracted along with recommendations on how to address them. The recommendations are structured around a framework developed for practical use in building projects. For ease of use, the nine key challenges are presented on a general level, with references to detailed recommendations. The framework is intended to be used to reduce the building technical risks of blue-green roofs, by addressing the most important quality risk elements.

Keywords: quality risk; blue-green roofs; risk management; building defects

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1. Introduction

1.1. Climate Change and Urban Flooding

Climate change is manifesting itself in different ways in different regions of the globe [1]. In the Nordic countries, the most notable impacts of climate change include an increase in temperature, increased precipitation, and an increase in the intensity and frequency of intense rain events [2]. Such events bring a high risk of urban flooding, with the stormwater drainage systems becoming overloaded due to insufficient capacity, and generally being in poor condition [3]. The risk of urban flooding is exacerbated by a densification of cities, where an increasing fraction of ground surfaces are being paved [4]. As stormwater is prevented from infiltrating into the ground locally, there is a need for alternative detention and retention capacity such as green roofs, rain gardens, and bioretention planters to prevent urban flooding [5,6].

The challenges imposed on the built environment by climate change emphasize the need for climate adaptation of buildings [7]. Climate adapted buildings are defined as "Structures that are planned, designed, and built to withstand various types of external climactic stresses" [8]. This ideally includes both the climate in which the building is built and the climate the building is expected to meet in the future. For this article, climate adaptation in terms of stormwater management is the main focus.

One climate adaptation strategy to mitigate the risk of urban flooding involves local retention and detention of stormwater on roof surfaces [9]. Blue-green roofs are roof assemblies wherein live vegetation and various substrate layers are used for rainwater detention as part of a stormwater management strategy [10]. Blue-green roofs can be distinguished from conventional green roofs in that blue-green roofs provide a larger amount of detention (temporary storage) of stormwater in addition to existing retention (evaporation) capacities, enhancing the roof's ability to delay and reduce stormwater runoff [11]. However, this definition is not universal. Some use the terms "retention/detention-based green roof" instead [12], as they give a more distinctive and accurate description than "blue-green roof", but the latter term will be used throughout this article for its brevity.

1.2. Blue-Green Roofs

Blue-green roofs assemblies are typically mounted as outer layers on top of compact, flat roof structures. The principal layers of the blue-green roofs are the plants themselves, the substrate in which they grow, and the layers for water storage and drainage. Multiple conceptual variations exist for each layer, most notably in the method of water storage. Water storage may occur in the form of standing water filling cups or boxes (seen for instance in Hamouz et al. [13]), water absorbed in porous materials (described in [14]), or pooling directly on the roof membrane [15]. Figure 1 shows an example assembly of a lightweight blue-green roof where water is stored in cups formed in a plastic dimple membrane.

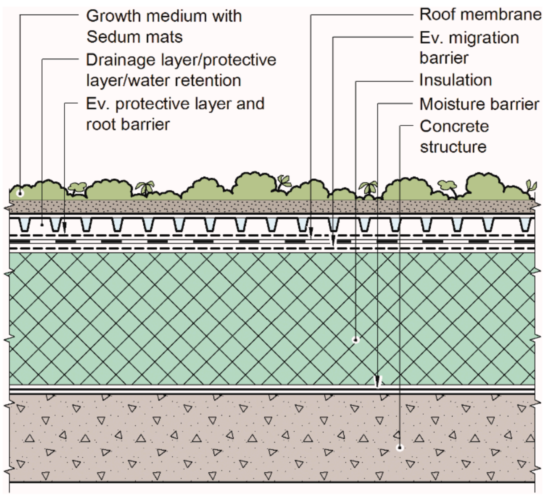

Figure 1. Example assembly of a blue-green roof mounted on a conventional, compact roof.

Green roofs may be built for several purposes other than urban stormwater management. Their purpose may also be to add green space to urban areas, or for energy savings in warm climates. The various benefits of green and blue-green roofs have been reviewed by several authors [16–20].

The addition of blue-green layers to a compact roof will change its physical operating conditions and add elements of quality risk. Most notably, the roof membrane is buried under the blue-green layers and will hence be unavailable for inspection once the blue-green roof assembly has been mounted. All layers in a compact roof have a very low water permeability, so water intruding through a defect may accumulate in the roof for months or years before any damage becomes visible on the internal side. This may allow defects to cause significant damage before they are discovered, as exemplified in [21]. For the same reason, the costs of membrane repairs for a blue-green roof will be substantially higher than for a conventional roof. Nevertheless, there are building technical advantages to blue-green roofs as well. The roof membrane is shielded from sun exposure, which limits ultraviolet degradation [22] and stabilizes the surface temperature of the membrane [23]. These various changed conditions represent an element of building technical risk that must be accounted for in the planning, construction, and operation of blue-green roofs for their benefits to be fully realized.

A review of the literature shows a lack of attention to the practical challenges associated with blue-green roofs [10]. The technical risks and challenges of green roofs have been given some attention in research literature, but not holistically as the primary focus of research. Porsche and Köhler [24] reviewed life cycle costs of green roofs and mentioned some concerns of their durability and life span, but without going in detail on defects. Björk [22] investigated the effect of green roofs on roof membrane durability, but only in the context of the aging and decay of materials. Wilkinson et al. [25] reviewed technical considerations of blue-green roofs in Australia, charting perceived risks on a conceptual level as "barriers to uptake". Thodesen et al. [26] described the main challenges in adapting blue-green roofs to a Nordic climate. There is evidently a need to gather known information on the technical challenges, risks, and defects of blue-green roofs across several disciplines, organized in such a way that it becomes useful to practitioners in the building sector.

1.3. Risk and Building Defects

The building of a blue-green roof is a complex process involving several technical disciplines both in the planning, design, and construction phases. The different viewpoints of the various disciplines do not necessarily overlap to create a complete picture for risk management [27].

Risk is commonly described as a combination of the (primarily negative) consequences of events and their probability of occurring [28]. Quality risk, sometimes called technical risk, relates to the risk of occurrence of building defects. The term is neither universally adopted nor rigidly defined. In this article, quality risk is understood as "the likelihood of the occurrence of building defects, and their consequences on the building's quality". Quality is defined as "meeting the legal, aesthetic, and functional requirements of a project" [29]. The direct financial aspects of risk are not directly considered in this article, nor are personal safety risks.

Building defects are known to have a large impact on the economic activity of the building sector. Government reports and whitepapers from, for instance, the United Kingdom [30] and Norway [31], highlight the prevalence of defects in the building sector and an ambition of reducing their prevalence. However, the prevalence of building defects has not been fully understood or charted, presumably because of a lack of data [32]. It has, however, been estimated that building defects account for 10% of the turnover in the Danish construction sector [33]. In Australia, it has been estimated that defect costs account for 4% of the contract value of new dwellings [34]. Schultz et al. [35] list several other estimates of defect costs, most finding that extra costs related to defects comprise between 2.4 and 12% of the total costs of a project. In Norway, despite ambitions and a government mandate, a national database of building defects has not been established (the latest mention of such a database in research literature dates to 2009 [36]).

Certain trends can however be observed in research conducted on limited datasets of building defects that are compiled by single actors such as insurance companies or consulting engineers. Gullbrekken et al. [37] examined defects in roofs in Norway and found that precipitation moisture was the primary cause of damage in 49% of investigated cases. For compact roofs, 73% of examined defects were caused by precipitation or condensation of moisture. The relative number of compact roof defects attributed to precipitation moisture was found by Bunkholt et al. [38] to have increased over the past decade, for a complex variety of reasons. In addition to compromising the quality of the building, building defects represent an element of resource inefficiency and poor sustainability. The repair of defects requires materials and work hours additional to what is necessary to construct the building. This is both a waste of resources and a source of literal waste, both of which place unneeded strain on the environment [39].

In their review of technical considerations for green roofs, Wilkinson et al. [25] noted a need for professionals from several disciplines to cooperate to arrive at optimal design solutions for green roofs. It is evident that systematic and multidisciplinary management of moisture protection in roofs will be imperative to reduce the quality risk of blue-green roofs.

1.4. Research Questions

Addressing the general problems outlined above, this article will examine the following research questions:

- What are the main quality risks associated with blue-green roofs?
- In which stages of the building process may the different quality risks be mitigated?
- What are the main challenges to be addressed by a quality risk reduction framework?

The work has primarily been carried out in a Norwegian context to exemplify the framework approach to a specific setting. However, the framework is believed to be valid for blue-green roofs across cold-climate regions in general, both for new builds and renovations. A limitation of the study is that risks pertaining to personal injuries, costs, or delays in the building process are not covered. Blue-green roofs are multidisciplinary structures, and the perception of risk may be influenced by the perspectives and biases of the authors. Notably to this work, bias may influence the perception of which challenges to give priority in a risk reduction framework and should thus be noted. The background of the authors of this article is primarily that of building science, except co-author Tone Muthanna who specializes in hydrology.

2. Theoretical Background

2.1. Risk and Quality Risk

To effectively manage risk, one must first establish a definition of the term to use as a baseline for the work. There exists a multitude of proposed definitions of risk, but none appear to be universally adopted [40]. ISO 31000:2018 [41] defines risk as "the effect of uncertainty on objectives". The Project Management Institute defines uncertainty as "An event that, if it occurs, has a positive or negative effect on a project's objectives" [42,43]. Note that in this definition, "risk" only encompasses the negative effects of uncertainty. The debate of whether risk and uncertainty are synonymous terms has been going since at least the 1970s [40], but in this article, the term risk is preferred. "Uncertainty" also covers the positive outcomes of risk, which are not considered in this article.

Quality risk is a type of risk related to building defects. Arditi and Gunaydin [29] define quality as "meeting the legal, aesthetic, and functional requirements of a project". A building defect is understood as a technical defect in the building that compromises the quality of components beyond what is expected from aging and use. These definitions form the basis of quality risk, which is defined in this paper as "the likelihood of the occurrence of building defects, and their consequences on the building's quality". Other terms synonymous or related to quality risk include "defect risk" [44,45], "quality deviations" [46], and "defect management" [47].

2.2. Blue-Green Roof Assembly

The term "blue-green roof" has not been rigidly defined. Generally, they can be considered a sub-set of green roofs (roofs covered in vegetation) that are designed and built specifically for the purpose of stormwater management. Proposed definitions that separate blue-green roofs from green roofs include that blue-green roofs provide retention (stormwater evaporation/transpiration) capacity in addition to the detention (delayed runoff) capacity of green roofs [13] or that blue-green roofs have additional water storage capacity beyond what is needed to sustain the vegetation [10]. However, as the term "blue-green roof" is not widespread or universally adopted, exact definitions have yet to be agreed upon.

Most blue-green roofs are assembled on top of compact roof structures. These are roofs without air gaps, consisting of sandwiched layers of insulation between the roof membrane and the load-bearing structure [48]. Compact roofs are generally air- and water-tight when assembled correctly, but moisture can still intrude in the form of precipitation or humid air condensation in the case of defects [37].

2.3. Common Roof Defects

Ingvaldsen [49] and Kvande and Lisø [50] define three categories of building defects: defects due to flawed building, defects due to lack of maintenance, and defects due to erroneous use. Various sub-categories exist for each category. "Process-caused building defects" comprise the two former categories, sans the sub-category "neglect of maintenance". It is generally held that process-caused defects will be dominant early in the building's life cycle, while use- or wear-caused defects will become more prominent as the building ages. This principle is generally illustrated with the "bathtub curve", although this model has received some criticism for not being generally applicable in practice [51].

The most prominent risk element to the long-term integrity of a building envelope is that of moisture intrusion [52]. Moisture fosters biological growth in organic materials that could in turn deteriorate materials and affect indoor air quality, may act as a solvent affecting the properties of materials, may cause corrosion, and may exert mechanical loads due to frost expansion or weight [53]. Moisture control strategies often use a two-pronged approach: (1) prevent water moisture from entering the structure, and (2) allow moisture that has entered the structure to dry out [54]. In compact roofs, drying is generally not considered feasible as the roof features a vapour-tight layer both on the external (the roof membrane) and the internal side (the vapour barrier). Preventing moisture from entering the structure then becomes all the more vital. In Norway, it has been found that 50% of all building defects are discovered more than 5 years after the building has been handed over to the owner [50]. However, note that this number includes defects that occur during the use phase of the building.

2.4. Norwegian Legislation

The Norwegian legal framework for buildings is described by Lisø et al. [55]. Governmental regulatory measures are grounded in the Planning and Building Act [56] and specified in the Technical Regulations, last updated in 2017 [57]. The regulations are given as performance-based requirements, meaning that the requirements are not affected by the solutions chosen to meet them. Other governmental regulatory measures include guidelines, circulars, and other official reports. Additionally, it is mandatory for a building project to verify these regulatory measures. Independent analysis is always required. Another means of verification is to confer with pre-accepted solutions, for instance those presented in the SINTEF Building Research Design Guides [58].

2.5. Actors in the Building Process

The design and construction of a building is a complex process involving a multitude of actors across several disciplines. The roles and responsibilities of the various actors depend on the chosen contract strategy, but a building project usually involves the actors illustrated in Figure 2. The figure illustrates a typical design-build (DB) model, but other models generally tend to include the same actors and principal activities.

Note that not every actor will be a stakeholder in every case of building defects. The question of responsibility for building defects depends on many factors, including the type of defect, when it occurs, and contractual obligations.

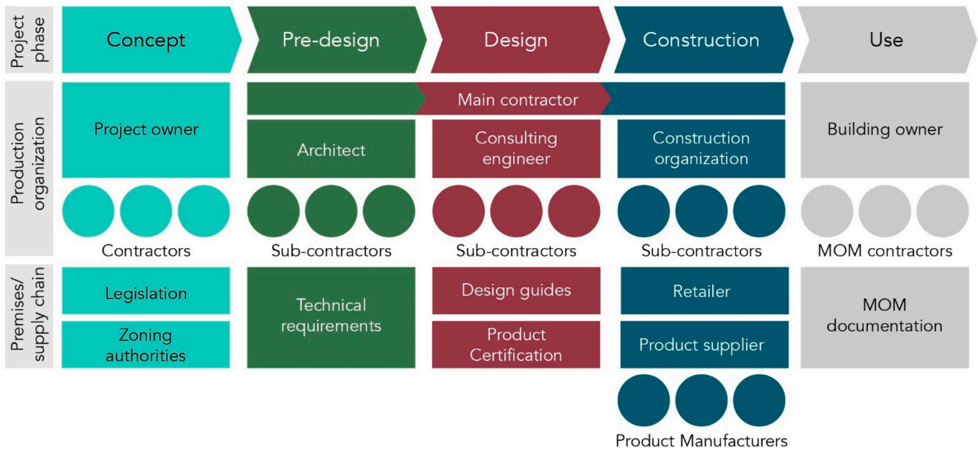

Figure 2. The phases and main involved actors in a building project, here illustrated for a design-build contract strategy. The figure is based on [59].

2.6. Requirements and Goals for a Quality Risk Reduction Framework

Requirements for risk management systems are outlined in the international standard ISO 31000 [41], while ISO 9001 [60] describes requirements for quality management systems. Central to the latter is the PDCA cycle, standing for Plan-Do-Check-Act. Quality management is thus a cyclical process in which methods are continuously evaluated and improved.

Grynning et al. [8] constructed a framework with a scope similar to the one described in this article, formulating four requirements a framework of this scope would have to meet, paraphrased here: (1) compliance with relevant national standards, (2) compliance with relevant ISO standards, (3) "*The framework should be generic and thus applicable at all scales and for all actors* (. . .)", and (4) The framework should be specifically applicable in a national context.

Examples of risk reduction frameworks in use in Norway include the Norwegian standard for moisture safe design [61] and guidelines for procurement of climate-adapted buildings [62]. Both documents highlight the importance of procedures and communication about main concerns across disciplines. The level of detail in a guideline may be relatively low, as it is more intended as a tool to coordinate disciplines rather than teach the disciplines.

2.7. Information Perception

A subject that has received little attention in engineering design literature is the limitations to the capacity of the human brain when it comes to absorbing, retaining, and being able to remember large amounts of information. However, the capacity of working memory has been extensively studied within the field of psychology [63]. It is indicated by [64] that the human brain struggles to effectively process information when presented with more than 100–150 data points at a time. Guidelines that attempt to be as comprehensive as possible may thus end up becoming too cumbersome for practical use, particularly if they are intended for use among non-professionals in the disciplines they address. A multi-disciplinary guideline will hence need to be simple and get its main points across as easily as possible since, by definition, most of its information will be outside the main field of expertise of its readers. Sorting the information into a limited number of elements or categories is helpful to make information easier to process. It is indicated by Miller [65] and Saaty and Ozdemir [66] that the upper limit on human capacity to reliably process information on simultaneously interacting elements is seven, plus or minus two elements. It is therefore sought to keep the number of main categories in the quality risk reduction framework within this range.

3. Methods

This article summarizes the main conclusions of a PhD research project concerning risks assessment of blue-green roofs. Blue-green roof quality risk elements were identified and assessed through a combination of different methods, outlined in the paragraphs below. The overall purpose of the work is to comprehensively assess building technical quality risk elements for blue-green roofs across several technical disciplines and relevant project phases, and to address the risk elements through a risk reduction framework.

The quality risk reduction framework for blue-green roofs aims to provide a tool or a checklist to consult in the various phases of the building project. It is designed to be simple to use while also covering most practical aspects of the roof construction. As such, it is not intended to comprehensively address the minute details of roof design and construction—as this is already covered by, e.g., the SINTEF Building Research Design Guides—but rather guide the user towards information relevant to the topic and project phase in question. It is therefore to be used as a supplement to existing literature rather than a replacement.

3.1. Literature Reviews

The research was guided by the results of an initial, extensive literature review of green roof research [10]. A scoping study [67] was conducted across five scientific databases, identifying 100 articles for in-depth study. The literature review identified a general lack of literature concerning the service life, resilience, durability, or technical risks of green roofs, although many of its articles contained useful information of one or more practical aspects relevant to risk management.

Seven defect cases for compact roofs and green roofs were qualitatively examined. The sample is limited by the availability of in-depth case descriptions in English and Norwegian. It was sought to find defect cases for green and blue-green roofs, but no domestic results could be found for green roofs and no international cases for blue-green roofs. Given the novelty of blue-green roofs, this lack of data is to be expected. General lessons from the defect cases have been incorporated in the Results section.

Risk reduction frameworks in other, related disciplines were also studied to better assess how a risk reduction framework for blue-green roofs would appear. A small scoping study, following the methodology outlined by Arksey and O'Malley [67], was also conducted on the topic of quality risk.

3.2. Semi-Structured Interviews

Seven actors representing various disciplines in the Norwegian building sector were interviewed to obtain a qualitative understanding of the common defects and challenges observed on green roofs and other compact roofs. Semi-structured interviews were carried out over the phone or in person, and were loosely formed around a set of questions mailed to respondents ahead of the interviews, an approach called grounded theory [68]. The represented organizations included two public property developers, an insurance company, a material supplier, and a governmental advisory body. The individuals all had many years of experience in construction or material science and knowledge of the practices in the Norwegian building sector. Two of the individuals were involved in a major defect case on the roof of a university building. Information learning from the interviews were published in a separate article [69]. The interview scheme is attached to this article as Appendix B.

3.3. In-Depth Study of National Recommendations

In Norway, a common tool to aid building design is found in the Building Research Design Guides issued by the research organization SINTEF. The SINTEF Building Research Design Guides is a list of some 800 guideline documents (a number varying constantly as outdated design guides are updated and may be split from or merged into other guides) detailing design principles, practical experience, and construction techniques for various individual building elements. Comparable document series found abroad are the Danish BYG-ERFA series [70], the Finnish Rakennustieto [71] or the moisture safe design guidelines by the Swedish RISE [72]. While no single design guide covers blue-green roofs, principles for their design and construction may be gleaned from other guides on similar topics, such as the design guides for compact roofs, roofing membranes, Sedum roofs, and terraces.

The list of SINTEF Building Research Design Guides was assessed and nine design guides relevant to compact roofs and green roofs were chosen for in-depth study. Each of the 337 paragraphs of text in these design guides was labelled according to the main topic of its subject. Concerns and recommendations for compact and green roofs were grouped into 12 categories, which were later reduced to nine following discussions with experts and the recommendation from psychology literature [65] to keep the maximum number of main elements lower than 10.

The recommendations were also sorted according to the project phase for which they had the greatest relevance. This grouping of recommendations was used to create a draft for the risk reduction framework table.

It was noted that the existing guidelines made little distinction in their grouping of information, with recommendations sorted by building element rather than by project phase or discipline. This lack of sorting may make the large number of individual recommendations difficult to process in a practical fashion, as is suggested by psychology literature [64]. The issue of information overload in the SINTEF Building Research Design Guides has been treated in a separate study [73].

3.4. Identified Challenge Categories

It was chosen to organize the challenge categories as listed in Table 1, elaborating on categories defined by Skjeldrum and Kvande [74] as well as SINTEF Building Research Design Guides. While the categories may be closely related to the various disciplines and areas of responsibility in a project (e.g., structural loads being the chief concern of the structural engineer) it is chosen not to label them as such, to prevent a situation where a reader of the framework will only focus on the content sorted under their own area of responsibility. Several of the listed concerns interface with several disciplines, for instance, the question of the water storage capacity of the roof. This design load will be a main concern both from a hydrology and structural engineering perspective and vital to guide further design decisions in both disciplines throughout the project.

Table 1. Topic categories for attentions in the quality risk framework.

Category	Description
Blue-green functionality	Retaining the retention and detention functionality of the roof. Survival of plants.
Organization	Issues related to the project’s sub-processes, participants, and coordination thereof.
Material integrity	Retaining the integrity of the materials used in the roof, most crucially the roofing layer.
Moisture-proof design	Creating a roof design based on building physical principles and safe from moisture problems other than those caused by leaks.
Drainage and drains	Ensuring that water leaves the roof without causing issues. “Drainage” refers to the path of the water from where precipitation lands until it reaches the drains, “Drains” covers the drains themselves and the downpipes connected to the roof.
Structural loads and wind	Mechanical forces acting on the structure. Wind flow may generate low pressure areas, which may loosen materials.
Fire protection	All issues related to fire.
Maintenance	Maintenance and maintainability of the roof.
Environmental issues	Concerns about the environmental performance of the roof, including pollutants, biodiversity, and waste disposal issues.

3.5. Joint Workshops with Experts

An initial outline of the framework was compiled by the authors based on recommendations from the building design guides, the results of the literature study, and the qualitative findings from the interviews. A joint workshop was then arranged, featuring experts from different disciplines related to building science and civil engineering. The participants included the authors, a consulting engineer of building physics, two experts in stormwater management, and two experts in property development and operation. The goal of the workshop was to provide feedback on and refine the framework in a qualitative manner. Participants were shown the initial outline of the framework in advance of the workshop and encouraged to discuss its content and provide suggestions for its improvement. The ninth topic category, environmental issues, was added as a result of this workshop.

4. Results

4.1. Critical Points in Blue-Green Roof Design and Construction

Figure 3 illustrates the main points of weakness for a blue-green roof, based on interviews and literature. Interviewees noted that material failure was a somewhat uncommon occurrence, barring wrongful use of the materials. Complex transition details, such as transitions between the roof and parapets or adjoining walls, were noted as common locations of leaks. Roof leaks may also appear around perforations in the roofing membrane, such as drains or fastening points for equipment. Another common location of moisture intrusion into roofs is the top of parapets. Areas with high traffic (illustrated with a person in Figure 3) may also take damage over time, although this is mainly confined to the upper layers of the blue-green roof, i.e., the plants themselves.

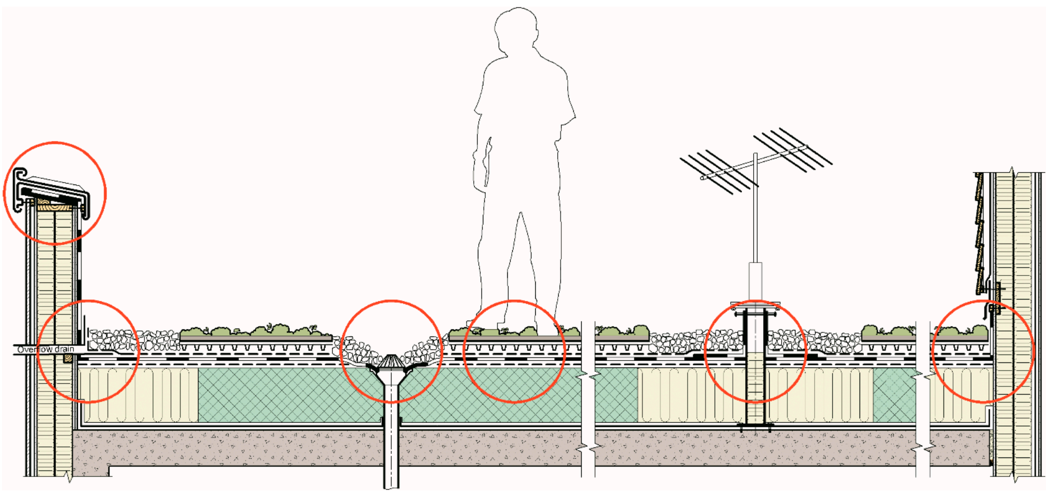

Figure 3. Overview of risk elements for green and blue-green roofs. Main details susceptible to defects are circled. They are, from left to right: flashings along the top of parapets, transitions between parapet and roof, drains, areas of high traffic, mounting systems for technical equipment, and transitions between the roof and adjoining walls, including doors.

4.2. Outline of the Risk Reduction Framework

Results from the literature were sorted according to the identified challenge categories and to the research phase in which they have the greatest relevance. The resulting matrix is forming the basis of a quality risk reduction framework, in the form of a "checklist" to be consulted when making key decisions in a blue-green roof project. The principal structure of the risk reduction framework is presented in Figure 4. For a full description of the categories, see Table 1.

Categories / Project phase	Concept	Pre-design	Design	Construction	Use
Blue-green functionality	• Evaluate ... • Etc. • ...	• Determine ... • Etc. • ...	• Select ...	• Schedule ...	• Establish ...
Organization	• Assess ...	• Involve ...	• Verify ...	• Inspect ...	• Review ...
Material integrity	• Estimate ...	• Determine ...	• Choose ...	• Perform ...	• Assess ...
Moisture-proof design	• Assess ...	• Identify ...	• Review ...	• Control ...	• Inspect ...
Drainage and drains	• Estimate ...	• Identify ...	• Develop ...	• Control ...	• Control ...
Structural loads and wind	• Estimate ...	• Identify ...	• Determine ...	• Avoid ...	• Evaluate ...
Fire protection	• Assess ...	• Define ...	• Define ...	• Perform ...	• Remove ...
Maintenance	• Estimate ...	• Establish ...	• Detail ...	• Document ...	• Follow ...
Environmental issues	• Define ...	• Assess ...	• Demand ...	• Ensure ...	• Avoid ...

Figure 4. Principal outline of the presented quality risk reduction framework. The project phases are defined according to Figure 2.

The following sections outline the identified challenges and quality risks of blue-green roofs as expressed through the nine challenge categories. They summarize the main content of the risk reduction framework, which is attached as Appendix A to this article. In the appendix, the results are formulated as checklist items and sorted according to project phases.

4.2.1. Blue-Green Functionality

Quality risk challenges in this category include the growth/survival of plants and the stormwater management capabilities of the roof. It was found by MacIvor and Lundholm [75] that the selection of plants to grow on the roof greatly affects both of these concerns. Native plants generally have generally been found to have better survivability than non-native plants. The selection of plant species was also found by [75] to have an influence on stormwater detention, although the difference between species may be less significant than the capacity of the water storage layer of the blue-green roof.

The assembly of the roof is critical to its survival in the early phases. Sedum roofs are usually delivered as mats of live vegetation stacked on pallets, a state in which the plants will not survive for long. It is imperative that the roof is assembled on the day of its delivery; therefore, project managers should be very careful to schedule the delivery so that the construction site is ready to receive and assemble the roof immediately [76].

Maintenance of the roof is also critical. The German Research Society for Landscape Development and Landscape construction (FLL) recommends 2–4 maintenance procedures per year, even for extensive green roofs [77]. The roof must be designed and built to accommodate regular access by maintenance personnel, and a maintenance plan must be made and followed. Irrigation systems may also be necessary, depending on the climate. Note that wind may dry out roofs even in cold and wet climates.

4.2.2. Organization

This category concerns the organization of the blue-green roof project and the relations between the involved actors. Many different disciplines are involved in the design and construction of a building roof, so coordination is essential to avoid misunderstandings or conflicts of interest. Mitigating measures may be instated as early as in the choice of contract strategy for the project. Defining a matrix of responsibility and appointing a roof manager for the project helps clarifying interface problems between disciplines during design and construction.

Among the two cases of complete collapse of green roofs found among the case studies, one in Hong Kong was found to originate from poor organization of the roof's construction. Unclear building instructions and responsibility interfaces caused the roof's as-built weight to greatly exceed what was originally designed [78].

4.2.3. Material Integrity

This category comprises defects caused by material failure. Interviewees noted that properly designed and built roofs rarely experience material failure, but improper use or assembly of materials may lead to their design specifications being exceeded. A common defect seen in compact roofs is leaks along seams between roofing sheets. This is more common in corners or along edges than on a flat roof, due to the geometry being more challenging for the roofer to work with [79].

Leaks are also somewhat common around perforations in the roofing membrane, e.g., drains or fastening brackets. While these can be made waterproof, and usually are, having a high number of them on a roof will increase the risk of leaks occurring.

Repairs costing tens of millions of Euros were caused by water intrusion through fastening systems and parapets in a Norwegian university building [69]. The building had been designed with exposed and visible ventilation equipment on its roof, as an architectural signal of the technical specialization of the university campus. This choice increased quality risk substantially, as the equipment had to be fastened at thousands of points perforating the roofing membrane. Even assuming a leak rate as low as 0.1% per fastening point, the roof would still be statistically expected to have several intrusion points for moisture spread across its roof—which also turned out to be the case in practice. With this probability of failure, a roof with only a hundred perforations would only have a 1-in-10 probability of containing an intrusion point at all.

Damage to the roof membrane itself may also occur during the construction and use phases. Several interviewees stressed the importance of keeping the roof clean of debris. Small, sharp objects like screws, metal clippings, washers, or pebbles may be dropped by workers on the roof, or stuck underneath the soles of shoes, and perforate the roofing membrane if stepped on. Such a defect will be particularly difficult to discover in a blue-green roof post assembly as it will be hidden underneath the blue-green layers. It is therefore of vital importance to ensure the integrity of the roof before and during the assembly of the blue-green layers. If the roof is designed and assembled correctly, the potential for roof membrane damage is drastically decreased after full assembly, as the membrane is shielded from exposure. A watertightness test of the roof is recommended before the blue-green layers are assembled, to make sure of the integrity of the roofing before it is buried.

4.2.4. Moisture-Proof Design

This category comprises moisture damages not caused by material failure. Notably among these is defects where running water passes around the roofing. This is usually caused when the membrane fold along parapets and adjoining walls is too low, combined with water pooling on the roof. Wind may then drive the water up against and over the fold [79]. Terrace doors level with the terrace are particularly susceptible to this type of water intrusion. Driving rain may also push rain droplets through joints and underneath drip edges in flashings, causing water intrusions around parapets.

Leaks of indoor air into the roof is another notable cause of defects in compact roofs [79]. A case was found wherein condensation of humid indoor air ruined a compact roof within 15 years of the building's construction, to the point that a complete renovation had to be carried out [21]. Hutchinson [80] describes a case wherein condensation of water vapour in indoor air caused significant rot to a compact wooden roof in Chicago. One root cause of the defects was a notable lack of awareness of the basic principles of building physics. The case makes evident that information which may increase or mitigate risks may not always be known to those involved in a project, despite being publicly available.

4.2.5. Drainage and Drains

Water pooling on the membrane due to insufficient drainage sloping is also considered a defect, which may not in itself cause damage to the building but has the potential to cause or exacerbate other defects. Overflow drains are essential, but incorrect installation may also cause defects. The drain seen on Figure 3 is arguably placed too low, making it difficult to waterproof by using a sleeve. Its low placement also causes water to flow through it in unintended situations, such as when wind pushes roof water up against the parapet. As overflow drains are mainly intended as an emergency measure, the façade beneath the drain is rarely protected against soiling or discoloration from dripping water.

A defect specific to cold climates is that of ice build-up, forming icicles or ice chunks that pose a risk to passers-by beneath the roof. It is caused by snow being melted by the heat flux through the roof, and re-freezing once the snowmelt runs away from the heated part of the roof, e.g., eaves or overhangs. The phenomenon may also create a dam of ice, creating a large pool of snowmelt on the roof, which may cause water damage or even a risk of structural failure [81]. It is not known to what degree blue-green roofs are vulnerable to ice build-up, as no literature has been found on the subject.

The second case of complete collapse of a green roof in literature was caused by drainage failure. Snowmelt from a roof overhanging a green roof overflowed from the roof gutter falling onto a section of the green roof where it re-froze, and ice piled up over time. The roof's capacity was finally exceeded by a heavy snowfall on top of the ice, followed by rain [82].

A peculiar case of a compact roof collapsing was found in Norway, caused by the weight of accumulated rainwater after an errant football had blocked the singular drain on a flat compact roof [83]. A simple leaf grate or emergency overflow drain would have been sufficient to prevent this collapse case, highlighting the risk inherent in systems with single points of failure.

Insufficient design and operation of an advanced roof downpipe system caused flooding and large moisture damages in a Norwegian school building [84].

4.2.6. Structural Loads and Wind

The weight of a green roof is perhaps the quality risk issue that has received the most attention in investigated literature. Especially for retrofits, adding extra mass to the roof may present the risk of deformations, drainage failure, and in extreme cases, collapse. It is crucial to account for the expected load from the blue-green roof—including the weight of detained water and snow if applicable—and the capacity of the structure from the early stages of the design process. Fortunately for the management of quality risk, structural loads are quantifiable and can be designed for, unlike for instance the risks of leakage, poor workmanship, or faulty maintenance.

In the investigated cases of roof collapse [78,82,83], collapse was not triggered during normal states of operation, but because the loads imposed on the roof greatly exceeded design levels due to accidental circumstances. The root causes of collapse were not caused by poor structural engineering, but by poor communication or compromised drainage.

The impact of wind on the roof should also be analysed. Wind suction may pose a challenge, particularly along roof edges and in corners, where it may be advisable to weigh down the green roof with ballast or a mechanical attachment [76].

4.2.7. Fire Protection

Green roofs are seen to be adequately resistant to sparks and radiated heat [76,77]. To mitigate the spread of fire, a gravel belt may be established along the edges of the roof. This also helps weigh the roof down against wind and prevents plant roots from reaching the edge folds of the roof membrane. Dead plants and dry leaves should be removed from the roof as part of regular maintenance.

If the blue-green roof is used as part of a public green space and accessible to visitors, an evacuation plan for the roof must also be established. Local fire codes may impose additional requirements and should always be consulted.

4.2.8. Maintenance

Proper maintenance is imperative to the long-term operation of a green roof [77]. The roof needs to be designed with maintenance in mind, including access for maintenance personnel. Green roofs require extra maintenance in the establishment phase, typically the two first years of operation.

It was noted by interviewees that roofs that are not visible from vantage points nearby are susceptible to maintenance failures—eventual defects such as dead plants or pooling of water may not be noticed.

4.2.9. Environmental Concerns

While not necessarily a defect in the traditional sense, it is important to note environmental concerns of the green roof as this does influence its quality. Primary concerns are biodiversity (avoid the use of black-listed species of plants [85]), seepage of pollutants from roof runoff, and the deposit of construction waste such as packaging.

Preliminary research on carbon emissions associated with building defects—primarily caused by the energy requirements for building dryers—suggest that the carbon emissions associated with building defect repairs are large and under-estimated [39]. Ensuring a defect-free roof may thus arguably count as a sustainability measure.

4.3. Roof Defect Responsibility

Comprehensive statistics on the root causes of roof defects could regrettably not be found. Anecdotally, two of the interviewees who were working with roof defects claimed to have experienced in their work an approximately even split between design flaws and build flaws. Other interviewees with experience in green roof assembly noted that it was uncommon for them to arrive to a swept and cleaned roof on the day of assembly.

The examined case studies show defects originating in different phases and disciplines, without any clear trend evident in the small sample size. However, one can note a general lack of coordination between disciplines in the defect cases. Several defects could have been avoided if information known to one actor had been available to guide the decisions of another. Perhaps most notable was the case described by Hutchinson [80], where basic mistakes of building physics caused and exacerbated severe damage to a compact wooden roof. The damage could have been avoided if the roof contractor had consulted known information about moisture safe design. This case highlights both the need and the potential for widely available and understandable guidance documents to help reduce the number of defects in the construction sector.

4.4. When Defects Occur

Defects may originate in any stage of the construction process (as described in Figure 2), even on the concept stage. For instance, a chosen roof concept may necessitate a high number of perforations or challenging geometries, leading to an increased quality risk compared to a more conventional concept. Such a failure of concept was observed in one of the case buildings [69]. The main stages in which defects can be said to originate are the pre-design, design, and construction stages. However, measures may be taken in earlier stages to mitigate the risks, for instance by selecting a design with fewer potential points of failure, or one that is easier to build. Flaws can also be mitigated or corrected in the use phase, through maintenance or adapting the use to the design's tolerance limits. Once again, there is evident a need for decision-makers to consult information from several disciplines to avoid decisions that increase the quality risk of the project. The risk reduction framework is hence presented as a matrix where checklist items are presented according to project phases as well as according to disciplines.

5. Discussion

This article has investigated the following research questions: What are the main quality risks associated with blue-green roofs, in which stages of the building process may they be mitigated, and what are the main challenges to addressing the quality risks through a risk reduction framework. The research questions are discussed separately in the paragraphs below.

5.1. What Are the Main Quality Risks Associated with Blue-Green Roofs?

The main quality risk associated with blue-green roofs is that of water intrusion into the roof structure. Recall the definition of quality risk as a synthesis of consequences and probability of defects. It is known from experience that water intrusion does occur in a substantial number of compact roofs—the probability of defects occurring is high. It is also known from the literature that defects in green roofs may be difficult to discover and expensive to repair, leading to high consequences should they occur. In sum, the risk associated with green roofs needs improved management. To reduce risk, it is therefore imperative to reduce the probability of water intrusion. According to the characterization of building defects by [50], three approaches are possible to this end: (1) avoiding flaws in design and construction, (2) conducting proper maintenance (mostly in the use phase, although maintainability needs to be considered in all the earlier phases), and (3) avoiding situations where the building's design parameters are exceeded (in the use phase). As can be seen, all the defect categories are heavily affected by the design and construction of the building, making these phases the most critical to the building's integrity.

5.2. In Which Stages of the Building Process May the Different Quality Risks Be Mitigated?

The greatest potential for quality risk mitigation lies in the pre-design, design, and construction stages of the project. With currently available data, it is not possible to point to any single participant or actor in a blue-green roof project to be statistically more at fault than any others. However, it is noted that most registered defects are well known both in literature and to the actors in the industry, as are the ways to mitigate them. The "correct solution"—or at least sound principles of design—for most conceivable building details is known information, and theoretically available to all participants in the project.

As such, the key question regarding roof defects is not "what goes wrong?", but "why does it go wrong?" Few construction projects venture into unknown territory in terms of design challenges. Building science has come far enough that building a compact roof does not require improvisation or guesswork. While roof construction may not be an exact science, the general principles for a moisture safe and defect-free roof have long since been identified. Yet, for various reasons, they are not always applied, and roof defects occur as a result.

Thus, it is not required of a risk reduction framework to advance the limits of knowledge of building science. Rather, it is to bridge the knowledge gaps existing within the body of known information and communicating known information to the actors who need to know it. This is seen for instance in the Norwegian standard for moisture-safe building design, whose main body of text only considers planning, procedures, routines, and delegation of responsibility rather than building physics [61].

Most notably, design concerns must be communicated between the various technical disciplines to find solutions that meet their various requirements. This is also true when weighing risk against functionality. A moisture-safe roof that fails to retain water is not an effective blue-green roof.

5.3. What Are the Main Challenges to Be Addressed by a Quality Risk Reduction Framework?

The research suggests that the challenges remaining to be solved regarding building quality risk do not lie on the technical level. The common types of defects and their causes are well known, at least qualitatively, as are the technical solutions required to meet them.

Instead, the potential to mitigate risk lies on the processual level. Raising awareness of the relevant challenges and issues may help avoiding basic, but impactful mistakes. This was also noted in earlier research, for instance by [25]. For instance, prioritizing membrane integrity during the construction process and performing a watertightness test. A framework may also help in telling which lines of communication will have to be established within the project.

How the process itself is controlled may also be improved. This may include a clarification of what types of decisions will have to be made by project leaders at the different stages in the process. The main component of the risk reduction framework, the matrix of key decisions, is presented in Section 4.2 and attached in full as Appendix A to this article.

6. Conclusions

The research shows that technical risks associated with blue-green roofs are numerous, but overall manageable. Technical issues are known in the building industry and described in technical and scientific literature. The most notable risk is that of water intrusion into the roof structure, which may happen as a result of several different defects, and is challenging to identify and repair. Weak points of green roofs that should receive extra attention during planning, design, construction, and maintenance include drains and emergency drains, fastening systems for roof equipment, and transitions between building elements such as the roof and its adjoining parapets and walls.

Many common risks relevant to blue-green roofs are shared with compact roofs, which have been studied extensively for decades. However, this presentation and application of knowledge is lacking, as risk elements are varying over a wide range of different disciplines and areas of responsibility. A good way to manage the risk appears to be lacking, as shown by the large number of defects found in compact roof structures to this date. Processual understanding may be the key to addressing these defects effectively.

The outline of a quality risk reduction framework has been presented, listing the main concerns related to quality risk in a blue-green roof project. It is applicable to new builds as well as retrofit projects. The framework is not meant to replace existing literature, but to serve as a supplement by highlighting the main concerns that will require further consideration to result in reasonably informed decisions. The framework intends to lead the user to seek information in the existing body of knowledge, for Norway this includes the SINTEF Building Research Design Guides or other national recommendations. It also intends to ease and clarify communication on key issues between actors and across multiple disciplines.

Future work will include refining the framework and to apply it in a blue-green roof project. The applicability of the framework should be tested for both new builds and retrofit projects. Lessons learned from the projects will be used to review, refine, and potentially develop new versions of the framework.

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Appendix A. Risk Reduction Framework Table

Table A1. Matrix of key actions in the risk reduction framework.

Project Phase Categories	Concept	Pre-Design	Design	Construction	Use
Blue-green functionality (incl. plant survival)	• Determine/evaluate whether a blue-green roof is appropriate for the project • Define strategic goal of the roof (i.e. aesthetics/stormwater/"environmental scoring") • Determine strategy for roof water reuse	• Determine whether the roof shall provide retention or just detention • Select water storage concept • Evaluate concept according to maintainability (i.e., roof access)	• Selection of plants and substrate to suit conditions of the roof (shading, traffic, wind, temperature, etc.)	• Fit the delivery and immediate assembly of plants into construction schedule • Assemble the roof immediately upon delivery	• Establish and follow up weeding/maintenance plan • Consider service agreement with vendor • Replace dead plants periodically
Organization	• Assess the impetus for the roof (own initiative/regulatory) and how this may affect decisions • Evaluate alternative solutions—Is a blue-green roof mandated, or can stormwater management be handled better by other means? • Define the intended use of the roof • Choose contract strategy • Consider blue-grey roof if blue-green roof is not an option	• Involve relevant disciplines early in the decision process • Establish communication between disciplines • Define a matrix of responsibility, clarifying the interfaces between disciplines • Appoint a manager responsible for the roof	• Third-party/extended design verification • Determine what adaptations are necessary if the blue-green roof is removed from the project	• Third-party/extended inspection of the roof • Schedule delivery and assembly • Coordinate disciplines on site • Ready the roof for assembly of blue-green layers • Appoint personnel responsible for the roof (on site) and its readiness for assembly • Ensure awareness of the need for roof integrity among workers on site	• Periodic review of Maintenance—Operations—Management (MOM) plan

Table A1. *Cont.*

Project Phase Categories	Concept	Pre-Design	Design	Construction	Use
Material integrity (primarily roof membrane)	• Estimate the level of traffic/activity on the roof • Estimate the thickness and weight of the roof	• Determine roof structure design (conventional/inverted roof) • Project owner: specify the need for a watertightness test of the roof in contract documents	• Choose root protection, roof membrane, and insulation materials according to expected loads • Evaluate the need for "traffic zones" to be established on the roof • Design equipment bases and fastening points to avoid stretching the membrane • Consider the installation of moisture sensors to locate (future, potential) leaks • Ensure that selected materials do not react chemically	• Perform watertightness test before the assembly of blue-green layers • Protect the roof membrane from traffic and loads. • Consider temporary membrane protection • Clear and inspect the roof before blue-green layers are assembled	• Assess the impact of traffic over time and the need for further protection • Periodic inspections if possible, especially if operating conditions/loads are changed over time
Moisture-proof design	• Assess the complexity of the roof (geometry, number of roof surfaces, perforations, installations) • Identify equipment on the roof	• Identify all installations perforating the membrane • Identify all installations in the parapet/adjoining walls (including doors) • Identify flashings/façade transitions • Consider temporary covering of the roof during construction process	• Review membrane details (joints, overlaps, edges, and perforations) • Review special design details not covered in design guides • Review flashing details • Review thermal bridges	• Control and verify membrane transitions and edges.	• Periodically inspect membrane edges and perforations, if possible • Use thermography to chart condensation risk/leaks
Drainage and drains	• Estimate storage capacity needs/ambitions of water on roof	• Identify drainage pathways and connection to safe floodways • Specify the number of drains and emergency drains • Choose whether to build internal or external drains (or a combination) • Assess frost issues with the chosen solution	• Develop a schematic for roof sloping • Define protection against deformation (due to equipment on roof, traffic) • Design drainage layer to allow proper drainage • Determine placement of drains and emergency drains, including the height of the latter • Design drains for easy inspection • Use leaf grates and sand traps in drains	• Control the built solution against roof sloping schematic • Control drainage paths and deformations • Control drains including fastening/sleeves	• Periodically control drainage function • Periodically inspect drains for blockages (especially if extreme rain is forecast)

Table A1. *Cont.*

Project Phase Categories	Concept	Pre-Design	Design	Construction	Use
Structural loads and wind	• Estimate weight of roof • Estimate weight of water on roof • Estimate wind profiles due to roof shape • Estimate added weight due to maintenance equipment/traffic • Estimate added weight due to roof equipment needs	• Identify loads on the roof • Ensure that the relevant loads are included in the early structural design process.	• Determine total weight of roof, assuming full saturation (or even compromised drainage) • Specify insulation stiffness requirements • Determine "ballast effect" (wind resistance) of blue-green layers.	• Avoid storage of materials or equipment on the roof during construction • Assess the impact of wind during the construction period	• Evaluate and limit the maximum growth of vegetation • Inspect for water pooling due to clogged drains • Inspect for water pooling due to deformations • Evaluate roof vulnerability to wind under dry conditions
Fire protection	• Assess how the shape and placement of building affects fire concerns • Map main fire concerns	• Define evacuation plan (if roof is open to the public)	• Define measures against spread of fire across the roof. • Assess compliance of green roof assemblies with local fire codes		• Periodic removal of dead plants, dry leaves, etc.
Maintenance	• Estimate level of maintenance for the roof concept • Assess funding for maintenance	• Establish access for maintenance personnel/equipment • Owner: provide clear maintenance specifications in tender documents.	• Detail MOM plans • Determine type of root protection based on maintenance ambitions	• Document any changes between designed and built solutions • Verify compliance of material requirements	• Follow maintenance plans • Periodic inspections of roof
Environmental issues	• Define environmental ambitions of the roof	• Assess potential for/threats against biodiversity • Specify requirements for products, packaging, and processes	• Demand EPDs for all materials, including soil mix for substrate • Assess seepage of chemicals from materials	• Ensure responsible handling of waste on the construction site	• Avoid use of salts to de-ice traffic zones • Assess the impact of fertilizers in the roof runoff water

Appendix B. Interview Questionnaire

(Translated from Norwegian)

Part 1: General

1. What is your current position?
2. What is your background and work experience?

Part 2: Practical Quality Risk Management

(1) Do you experience that there are a lot of incorrectly executed roofs in Norway?
  (a) What usually goes wrong? Wrong people? Flawed specifications from the owner?
  (b) Have you experienced fake or fraudulent materials?
  (c) What is the extent of roof damages in Norway?
  (d) Composition of workers? How much depends on the construction crew?

(2) What are the common fault mechanisms for incorrectly executed roofs? What goes wrong when things go wrong?
  (a) Holes in materials, loose seams/joints, are the materials not waterproof, etc.?
  (b) WHEN do these flaws occur?
  (c) How much time do you have to discover the flaws before damage occurs?

(3) What characterizes incorrectly executed roofs? Structure, materials, which important materials are *not* used, etc.
   (a) Different operating conditions and prerequisites place different requirements for design/materials for the roofing. When something goes wrong, what requirements are most often not met?
(4) Have you experienced cases where it has been built correctly, but with the wrong materials?
   (a) How do you detect the error?
   (b) Can it go well?
(5) To what extent do you think that the current regulations ensure the use of the right roofing materials (prevents you from getting the wrong type of product on the roof)?
   (a) Are specific documents required to be attached?
   (b) If you were to quit your legitimate job and start as a thug in this sector [i.e., exploiting weaknesses in the current system]: Would it be easy to circumvent the regulations, for those who really want to?
   (c) Is anything/enough being done with those who are caught?
   (d) What if you discover defects too late?
(6) Do you perceive that the customers/clients work to investigate what kind of products they want/get?
(7) Proportions, what does a quality product (+quality control?) cost compared to a cheap product?
   (a) What is your perception of the cost of doing an extra quality check?
(8) What perception do you have of the control if the cheaper solution is chosen?
(9) How is the relationship with the competitors in the roofing sector? Do you perceive it as generally tidy?
   (a) Internal justice in the sector?

Part 3: Corporate Governance

1. How can the client protect himself against the use of bad or fraudulent materials?
   a. Increased degree of early involvement/interaction with potential suppliers?
   b. Use of incentives?
   c. Use of agreement regulators as max. supplier link/supply chain structure?
2. What influence does the client have?
   a. *Follow-up question:* How should the client proceed in case of suspicion of unwanted/sub-standard materials?
   b. *Follow-up question:* How can the project owner secure themselves against poor supplier choices?
   c. *Follow-up question*: How can the project owner follow up in the implementation phase?
3. Do you think the protection against such incidents is well enough implemented in projects that are carried out today?

Part 4: Control

1. What control mechanisms exist today to handle the flow of materials to the construction site?
   a. *Follow-up question:* Are specific documents required to be attached?
   b. *Follow-up question:* To what extent are background checks/checks carried out on suppliers?
2. Who is responsible for controlling the quality of the materials?
   a. *Follow-up question*: Who *should be* responsible?

3. What control mechanisms should be in place to handle the flow of materials to the construction site?

Part 5: Closing Questions

1. Do you know specific people, companies or organizations that we should contact regarding this topic?
2. Are there any aspects of these issue that are little or not addressed in the industry, and that may be interesting to examine in more detail?
3. Is it okay if we contact you again later, if there is a need for further inquiries?

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