

Risk Reduction Framework for Blue-Green Roofs

Erlend Andenæs ^{1,*} , Berit Time ², Tone Muthanna ¹ , Silje Asphaug ¹  and Tore Kvande ¹ 

¹ Department of Civil and Environmental Engineering, Norwegian University of Science and Technology, 7491 Trondheim, Norway; tone.muthanna@ntnu.no (T.M.); silje.asphaug@sintef.no (S.A.); tore.kvande@ntnu.no (T.K.)

² SINTEF Community, 7465 Trondheim, Norway; berit.time@sintef.no

* Correspondence: erlend.andenas@ntnu.no

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 climatic 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.

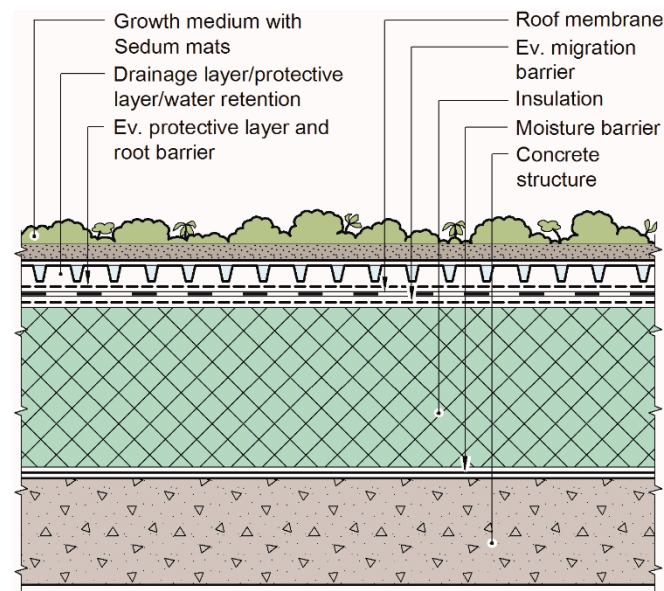


Figure 1. Example assembly of a blue-green roof mounted on a conventional, compact roof.

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.

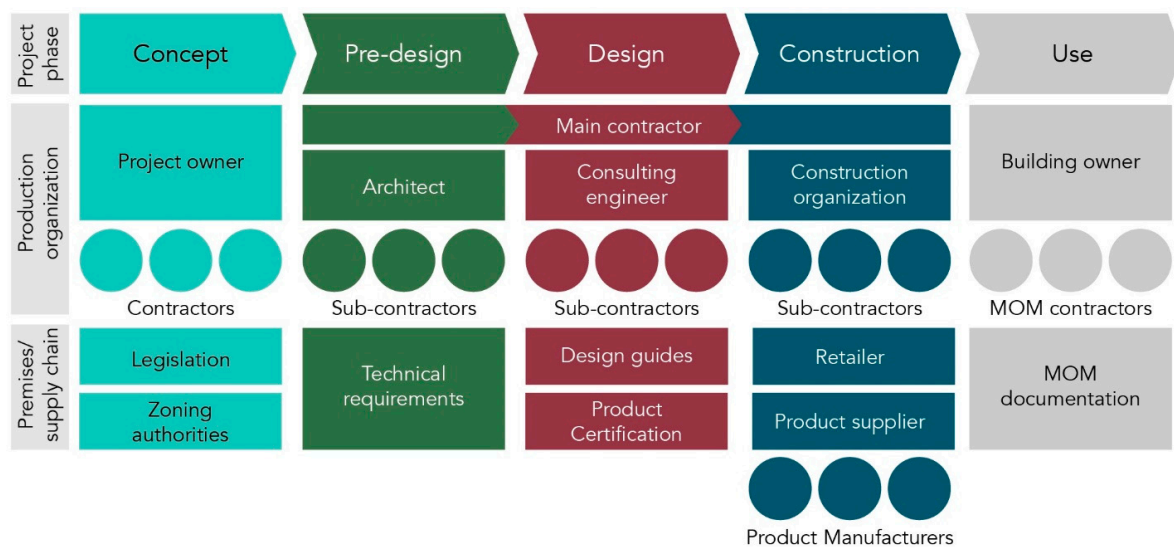


Figure 2. The phases and main involved actors in a building project, here illustrated for a design-build contract strategy. The figure is based on [59].

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.

Gynning 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.

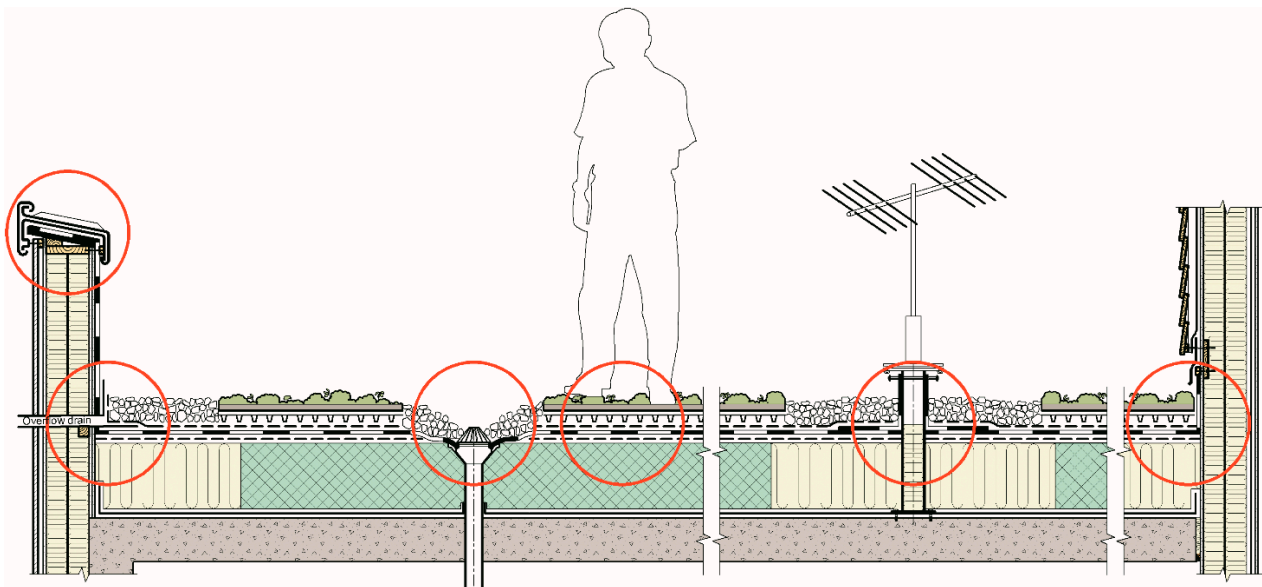


Figure 3. Overview of risk elements for green and blue-green roofs. Main details susceptible to defects are circled. They are, from left to right: flashings along the top of parapets, transitions between parapet and roof, drains, areas of high traffic, mounting systems for technical equipment, and transitions 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		<ul style="list-style-type: none"> • Evaluate ... • Etc. • ... 	<ul style="list-style-type: none"> • Determine ... • Etc. • ... 	<ul style="list-style-type: none"> • Select ... 	<ul style="list-style-type: none"> • Schedule ... 	<ul style="list-style-type: none"> • Establish ...
Organization		<ul style="list-style-type: none"> • Assess ... 	<ul style="list-style-type: none"> • Involve ... 	<ul style="list-style-type: none"> • Verify ... 	<ul style="list-style-type: none"> • Inspect ... 	<ul style="list-style-type: none"> • Review ...
Material integrity		<ul style="list-style-type: none"> • Estimate ... 	<ul style="list-style-type: none"> • Determine ... 	<ul style="list-style-type: none"> • Choose ... 	<ul style="list-style-type: none"> • Perform ... 	<ul style="list-style-type: none"> • Assess ...
Moisture-proof design		<ul style="list-style-type: none"> • Assess ... 	<ul style="list-style-type: none"> • Identify ... 	<ul style="list-style-type: none"> • Review ... 	<ul style="list-style-type: none"> • Control ... 	<ul style="list-style-type: none"> • Inspect ...
Drainage and drains		<ul style="list-style-type: none"> • Estimate ... 	<ul style="list-style-type: none"> • Identify ... 	<ul style="list-style-type: none"> • Develop ... 	<ul style="list-style-type: none"> • Control ... 	<ul style="list-style-type: none"> • Control ...
Structural loads and wind		<ul style="list-style-type: none"> • Estimate ... 	<ul style="list-style-type: none"> • Identify ... 	<ul style="list-style-type: none"> • Determine ... 	<ul style="list-style-type: none"> • Avoid ... 	<ul style="list-style-type: none"> • Evaluate ...
Fire protection		<ul style="list-style-type: none"> • Assess ... 	<ul style="list-style-type: none"> • Define ... 	<ul style="list-style-type: none"> • Define ... 	<ul style="list-style-type: none"> • Perform ... 	<ul style="list-style-type: none"> • Remove ...
Maintenance		<ul style="list-style-type: none"> • Estimate ... 	<ul style="list-style-type: none"> • Establish ... 	<ul style="list-style-type: none"> • Detail ... 	<ul style="list-style-type: none"> • Document ... 	<ul style="list-style-type: none"> • Follow ...
Environmental issues		<ul style="list-style-type: none"> • Define ... 	<ul style="list-style-type: none"> • Assess ... 	<ul style="list-style-type: none"> • Demand ... 	<ul style="list-style-type: none"> • Ensure ... 	<ul style="list-style-type: none"> • 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)	<ul style="list-style-type: none"> 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 	<ul style="list-style-type: none"> Determine whether the roof shall provide retention or just detention Select water storage concept Evaluate concept according to maintainability (i.e., roof access) 	<ul style="list-style-type: none"> Selection of plants and substrate to suit conditions of the roof (shading, traffic, wind, temperature, etc.) 	<ul style="list-style-type: none"> Fit the delivery and immediate assembly of plants into construction schedule Assemble the roof immediately upon delivery 	<ul style="list-style-type: none"> Establish and follow up weeding/maintenance plan Consider service agreement with vendor Replace dead plants periodically
Organization	<ul style="list-style-type: none"> 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 	<ul style="list-style-type: none"> 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 	<ul style="list-style-type: none"> Third-party/extended design verification Determine what adaptations are necessary if the blue-green roof is removed from the project 	<ul style="list-style-type: none"> 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 	<ul style="list-style-type: none"> 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)	<ul style="list-style-type: none"> Estimate the level of traffic/activity on the roof Estimate the thickness and weight of the roof 	<ul style="list-style-type: none"> Determine roof structure design (conventional/inverted roof) Project owner: specify the need for a watertightness test of the roof in contract documents 	<ul style="list-style-type: none"> 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 	<ul style="list-style-type: none"> 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 	<ul style="list-style-type: none"> 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	<ul style="list-style-type: none"> Assess the complexity of the roof (geometry, number of roof surfaces, perforations, installations) Identify equipment on the roof 	<ul style="list-style-type: none"> 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 	<ul style="list-style-type: none"> Review membrane details (joints, overlaps, edges, and perforations) Review special design details not covered in design guides Review flashing details Review thermal bridges 	<ul style="list-style-type: none"> Control and verify membrane transitions and edges. 	<ul style="list-style-type: none"> Periodically inspect membrane edges and perforations, if possible Use thermography to chart condensation risk/leaks
Drainage and drains	<ul style="list-style-type: none"> Estimate storage capacity needs/ambitions of water on roof 	<ul style="list-style-type: none"> 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 	<ul style="list-style-type: none"> 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 	<ul style="list-style-type: none"> Control the built solution against roof sloping schematic Control drainage paths and deformations Control drains including fastening/sleeves 	<ul style="list-style-type: none"> 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	<ul style="list-style-type: none"> 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 	<ul style="list-style-type: none"> Identify loads on the roof Ensure that the relevant loads are included in the early structural design process. 	<ul style="list-style-type: none"> 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. 	<ul style="list-style-type: none"> Avoid storage of materials or equipment on the roof during construction Assess the impact of wind during the construction period 	<ul style="list-style-type: none"> 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	<ul style="list-style-type: none"> Assess how the shape and placement of building affects fire concerns Map main fire concerns 	<ul style="list-style-type: none"> Define evacuation plan (if roof is open to the public) 	<ul style="list-style-type: none"> Define measures against spread of fire across the roof. Assess compliance of green roof assemblies with local fire codes 		<ul style="list-style-type: none"> Periodic removal of dead plants, dry leaves, etc.
Maintenance	<ul style="list-style-type: none"> Estimate level of maintenance for the roof concept Assess funding for maintenance 	<ul style="list-style-type: none"> Establish access for maintenance personnel/equipment Owner: provide clear maintenance specifications in tender documents. 	<ul style="list-style-type: none"> Detail MOM plans Determine type of root protection based on maintenance ambitions 	<ul style="list-style-type: none"> Document any changes between designed and built solutions Verify compliance of material requirements 	<ul style="list-style-type: none"> Follow maintenance plans Periodic inspections of roof
Environmental issues	<ul style="list-style-type: none"> Define environmental ambitions of the roof 	<ul style="list-style-type: none"> Assess potential for/threats against biodiversity Specify requirements for products, packaging, and processes 	<ul style="list-style-type: none"> Demand EPDs for all materials, including soil mix for substrate Assess seepage of chemicals from materials 	<ul style="list-style-type: none"> Ensure responsible handling of waste on the construction site 	<ul style="list-style-type: none"> 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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