From Inspection to Maintenance: A Visual Guide for Assessing Green Roof Conditions

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Sammendrag

Fra inspeksjon til vedlikehold: En visuell guide for tilstandsvurdering av grønne tak. Grønne tak gir miljømessige, økonomiske og sosiale fordeler og kan beskrives som takets funksjonelle tjenester. Deres langsiktige ytelse er imidlertid avhengig av vedlikehold. Begrenset forståelse av tekniske krav og vedlikeholdskostnader bremser utbredelsen av grønne tak, inkludert i Norge. Denne studien hadde som mål å utvikle en sjekkliste for inspeksjon av grønne tak i Trondheim og å identifisere visuelle indikatorer for defekter. Forskningen avdekket flere faktorer som bør inkluderes i sjekklisten for å sikre konsistente vurderinger. Det ble også utarbeidet en visuell veiledning for å vurdere tilstandsgrader, og dermed redusere subjektivitet. Fire grønne tak i Trondheim ble evaluert ved hjelp av sjekklistene. Resultatene avdekket defekter relatert til design og vedlikehold, selv om ett av takene viste bedre tilstand enn de andre. Retningslinjene som ble utviklet basert på inspeksjonene, bør oppdateres i takt med at flere grønne tak inspiseres. Dette vil redusere usikkerhet og forbedre påliteligheten i tilstandsvurderingene.

Summary

Green roofs (GRs) offer various environmental, economic, and social benefits, known as service functions. However, their long-term performance depends on appropriate maintenance. Limited understanding of technical requirements and maintenance costs hinders the global implementation of GRs, including in Norway. This study aimed to develop a visual inspection checklist for GRs in Trondheim and investigate visual indicators of potential failures. The research identified several factors for different GR components to be included in the checklist, promoting thorough and consistent evaluations. Additionally, a visual guide for assessing condition grades was proposed to limit subjective opinions. Four GRs in Trondheim were evaluated using the checklists, revealing various design and maintenance issues, although one GR was in better condition than the others. The proposed guideline, based on visual inspections of the four GRs, should be updated as more GRs undergo inspections, reducing uncertainties and improving condition assessment reliability.

Introduction

Green infrastructures (GIs) have over the decades become increasingly more relevant for managing stormwater in urban areas, as part of a sustainable adaptation strategy when facing climate change and increasing levels of urbanisation.

Climate change is exerting a severe impact on cities, increasing surface runoff due to more frequent and intense rainstorms, as well as coastal and river flooding. By 2050, over two-thirds of the world's population is expected to reside in urban areas (UN, 2019). As a result, cities must take considerable steps to mitigate the adverse effects of climate change. Urban planning will play a crucial role in the development and implementation of integrated strategies for both climate change mitigation and adaptation. GIs can play a key role in helping cities adapt to climate change by managing stormwater runoff and providing other essential ecosystem services (Pauleit et al., 2020).

Green roofs (GRs) are frequently asserted to offer various environmental, economic, and social advantages, referred to as service functions (Roghani et al., 2024). The reported advantages encompass a decrease in the urban heat island effect, urban air pollution, building energy consumption, stormwater runoff, and noise pollution, alongside an extension of roof material lifespan, enhanced conditions for urban ecology, augmented aesthetic and amenity value, and the provision of space for food cultivation (Berardi et al., 2014; Francis and Jensen, 2017; Kolokotsa et al., 2013; Nguyen et al., 2021).

The long-term performance of GRs, and other GIs alike, is contingent upon high-quality maintenance. However, the limited understanding of the technical requirements and associated maintenance costs presents a significant barrier to the widespread implementation of GRs on a global scale, including in Norway (Silva et al., 2015; Buøen, 2024). Recent surveying show that Norwegian municipalities often lack an overview of the costs associated with the GI maintenance and operation, and that GI maintenance vary a lot according to which department is responsible for the GI operation (Kolsnes et al., 2024).

Norway has established national standards for GRs, to ensure the product quality (NS 4417, Standard Norge, 2015a) and best practices of implementation (NS 3840, Standard Norge, 2015b). However, these standards do not include requirements for long-term operational data logging. As such, there is currently no standard approach for collecting data about the long-term condition and performance of GRs.

This study addresses this gap by identifying factors for inclusion in a visual inspection checklist for GRs. Four GRs in Trondheim were examined to develop a practical approach for inspectors to identify visual indicators of GR performance and potential failures.

Method

The factors necessary for creating a visual inspection checklist for GRs were built on the findings of Bahrami et al. (2024), who identified that GRs could fail at different stages of their lifecycle–design (D), construction (C), and user/maintenance (M). The design and construction phases are particularly important in preventing failures, as studies indicate that customizing GR designs to align with specific environmental conditions can enhance their ecological impact and hydrological performance (Fioretti et al., 2010; Penkova et al., 2020). Moreover, local climatic factors such as temperature, humidity, wind, and solar radiation significantly influence processes like evapotranspiration (Johannessen et al., 2018).

Building on this understanding, Buøen (2024) evaluated international maintenance guidelines from countries with comparable climate conditions to Trondheim, including Germany, the UK, Sweden, and Canada, as classified by the Köppen-Geiger climate classification (Mamen, 2023). Table 3 in Buøen (2024) summarizes maintenance guidelines for GR components across different standards, including the FLL (Forschungsgesellschaft Landschaftsentwicklung Landschaftbau; Landscape Research, Development, and Construction Society), GRO Code (UK), Grönatakhandboken, STEP, and Norwegian standards. Key recommendations include maintaining a vegetation free perimeter around openings, achieving over 85% plant coverage with minimal invasive species. Drainage layers should distribute rainwater evenly, and protective layers should overlap. Inspection and debris removal should occur bi-annually for most components and irrigation systems should be frost-protected.

These guidelines align with practices observed in cities like Vancouver and Seattle, which have developed manuals for monitoring the conditions of GI systems. The City of Vancouver utilizes data from GI monitoring to refine design and maintenance activities, adapting post-construction designs based on monitoring results to improve performance (Spraakman et al., 2024). Similarly, City of Seattle (2021) has developed a manual featuring images of GI components with varying condition grades, allowing maintenance personnel to schedule and perform maintenance tasks.

These practices, along with the findings from analysing cold climate maintenance guidelines, form the foundation for the proposed checklist presented here. This checklist aims to assist inspectors in identifying the condition state of GR components. The checklist categorizes condition grades, taking inspiration from existing condition classifications used in urban drainage asset management, for GR components into four distinct levels: (1) Poor, (2) Fair, (3) Good, and (4) Excellent. Each level corresponds to specific actions that maintenance personnel should take, ranging from "replacement needed" for those rated as Poor to "routine maintenance" for those classified as Excellent. This qualitative method relies on visual inspections, requiring minimal time from operators to conduct periodic assessments. It is not limited to GRs and can be expanded to include other types of GI, such as swales. The outcomes of the visual inspections can then be used to determine if more precise investigations are necessary, such as incorporating quantitative measurements (e.g., infiltration tests) or analysing sensor data.

Results and discussion

Constructing a visual condition assessment guide

To create a visual guide for assessing GR condition grades, four GRs in the city of Trondheim were inspected, and photographs of their components were taken. In the next step, the authors attempted to match each photograph with the corresponding condition grade to compile Table 1. It should be noted that, whenever appropriate photographs were unavailable, figures from other official resources were included. For example, images from the website of the STEP initiative (LID SWM, 2022) are incorporated in the first row of Table 1. It should be emphasized that this initial guide establishes a starting point for a more extensive and detailed documentation process. The focus in the guideline is currently on visual cues that can be seen when observing the GR, and the condition of the GR itself. Effects of GR condition on the building it is installed on (e.g. internal water damages) is not of scope for this study, but the inspection guidelines could be complemented by technical guidelines suited for this purpose (Andenæs, 2021). The checklist should be continually updated as more GRs undergo regular inspections, including those in different climates. This iterative approach will help reduce uncertainties and improve the reliability of condition assessments. In the future, inspections will expand the dataset, encompass a wider range of conditions and strengthening the overall objectivity of the guide.

Inspection of green roofs in Trondheim, Norway

Four GRs at different locations within the city of Trondheim were inspected. Details on each of them can be found in Buøen (2024). The GRs in each case study were evaluated individually using the developed visual guide presented in Table 1. Table 2 is color-coded to reveal the condition grades of different components in the studied GRs in Trondheim.

The inspection revealed several issues related to design and maintenance of the visited GRs.

Table 1. Suggested visual guide to aid in the assessment of GR condition grades. The pictures in red frames are sourced from LID SWM (2022) contributors, and not from Trondheim (as examples of these conditions were not observed during any of the four inspections).

	Condition grades			
GR components	**4 (Excellent)**	**3 (Good)**	**2 (Fair)**	**1 (Poor)**
Perimeter	 Vegetation-free zone around outlets (Photo: Vegetal ID from LID SWM (2022)).	 Vegetation-free zones along roof edges, lacking inspection paths in central roof area (Photo: Daniel Filippi from LID SWM (2022)).	 Vegetation within the vegetation-free zone.	 Vegetation damaged from foot traffic to the ladder
Vegetation	 Sedum is thriving and looking healthy.	 Weeds present on large areas of the roof.	 Areas of roof not covered in vegetation.	 Vegetation not attached to the substrate.
Growing medium	 Vegetation coverage is dense and uniform indicating growing medium with ideal drainage and nutrient content.	 Texture is fairly consistent, and no major signs of erosion	 Sedum not attached to growing medium, possibly due to inadequate properties.	 Growing medium completely eroded in this part of the roof.
Protective layers	 Filter layer runs well up on the edge.	 Filter layer with insufficient overlap can be critical around roof penetrations	 Filter layer with not enough overlap.	 Filter layer not overlapping, exposing drainage layer.
Overflow outlets	 Inspection chamber with cover, no flow obstruction.	 Inspection chamber with cover, dead vegetation obstructing flow.	 Inspection chamber without cover, trash and vegetation obstructing flow.	 No inspection chamber, outlet clogged by vegetation.

Table 2. Condition states observed in four case studies in Trondheim, Norway

Component	Visual indicators	Case studies			
		GR1	GR2	GR3	GR4
Perimeter	Vegetation free zone around roof penetrations	① Poor	② Fair	③ Good	① Poor
	Inspection path	① Poor	③ Good	④ Excellent	① Poor
Vegetation	Vegetation coverage	③ Good	③ Good	④ Excellent	④ Excellent
	Invasive species present	③ Good	③ Good	③ Good	④ Excellent
Growing medium	Signes of bare soil	③ Good	③ Good	④ Excellent	④ Excellent
	Signs of uplift	③ Good	② Fair	④ Excellent	④ Excellent
Protective layers	Enough overlapping	③ Good	③ Good	④ Excellent	∅ Not applicable
	Run up all edges	④ Excellent	③ Good	④ Excellent	∅ Not applicable
Outflow outlets	Debris and trash in outlets	② Fair	① Poor	④ Excellent	∅ Not applicable
	Debris and trash in gutters	① Poor	∅ Not applicable	∅ Not applicable	③ Good
	Damage and corrosion on components	② Fair	③ Good	② Fair	④ Excellent
Irrigation system	Protected against frost	④ Excellent	∅ Not applicable	∅ Not applicable	∅ Not applicable
	Damage and corrosion	④ Excellent	∅ Not applicable	∅ Not applicable	∅ Not applicable

④ Excellent, ③ Good, ② Fair, ① Poor, ∅ Not applicable

Vegetation free zones were available only in GR2 and GR3, where invasive vegetation had grown inside them. Invasive species were present inside vegetation areas as well, with the problem increasing in shaded areas of the rooftops. These species could impact vegetation health and clog drainage layers of GRs. The growing medium and protective layers in GR1 and GR2 lacked sufficient overlap in some areas of the roof, exposing the roof structure to weather conditions. GR2's location near fjord exposed it to extreme winds which had contributed to the uplift and separation of its layers, and wind erosion of soil particles. The windy conditions had also damaged the outlet structures on GR2, blowing the inspection chambers away. Uncovered outlets were often clogged by moss or vegetation accumulation, affecting the outflow rates from the roof. In comparison, outlets with chambers in place were in satisfactory conditions where moss accumulation was least observed. Irrigation systems were only available for GR1, while the other GRs relied solely on precipitation for watering the vegetation. The irrigation system was in good condition however, the water hose had been kept on the GR vegetation throughout the year, exposing it to freezing temperatures. While visual inspections can identify many surface-level defects, such as invasive species, bare soil, uplifted areas, and trash blocking the outlets, the method has limitations. Not all failures may be identified through visual inspection alone. For example, failure to improve runoff quality and reduce noise reduction requires more invasive techniques or specialized equipment to detect.

In the next step, an attempt was made to link the occurrence of defects in various components at different stages of the life cycle of GR (Table 3). As inferred from this table, the maintenance stage plays a significant role in keeping a GR in shape to deliver its designed purposes, and the majority of defects can occur during this stage. Accordingly, having a well-developed inspection procedure, along with a comprehensive maintenance program, is essential.

While practical and useful for identifying immediate issues, this approach lacks a quanti-

Table 3. Visual indicators of potential green roof failure and possible stage of occurrence (and identification)

Component	Visual indicators	Stages*		
		D	C	M
Perimeter	Vegetation free zone around roof penetrations	✓		✓
	Inspection path	✓		
Vegetation	Vegetation coverage		✓	✓
	Invasive species present			✓
Growing medium	Signs of bare soil	✓		✓
	Signs of uplift	✓		✓
Protective layers	Enough overlapping		✓	✓
	Run up all edges		✓	✓
Outflow outlets	Debris and trash in outlets			✓
	Debris and trash in gutters			✓
	Damage and corrosion on components			✓
Irrigation system	Protected against frost	✓		✓
	Damage and corrosion			✓
* D – Design stage, C – Construction stage, M – User/Maintenance stage				

tative dimension. The grading system used in the checklist is inherently subjective; different inspectors may interpret the same condition differently. Incorporating more objective, measurable data–such as moisture levels and load-bearing calculations–could enhance the analysis and provide more precise insights into the condition of the GRs. Quantitative assessments would also help mitigate some of the subjectivity that comes with visual inspections. For instance, a well-documented method exists for counting vegetation coverage as a percentage within a 10x10 cm grid over a 1 m^2 area, which could provide a standardized metric to complement visual evaluations (Hanslin and Johannessen, 2016). A possible way forward towards quantification could be either the usage of camera footage to enable automatization of the condition assessment process, similar to the pipe inspection automation (e.g., Haurum and Moeslund, 2020), or the direct measurement of plant health using infrared cameras (e.g., Zhang and Zhang, 2022).

Conclusion

This study aimed to develop a visual inspection and condition assessment guide for GRs and to investigate how visual indicators of defects can be identified and addressed at various stages of the GR lifecycle. Several factors were suggested to be included in the checklist to promote thorough and consistent evaluations of the GR's condition. These elements include maintaining vegetation-free zones around roof penetrations, providing inspection paths, ensuring adequate vegetation coverage, and monitoring for invasive species. Additionally, signs of bare soil and uplift, overlapping protective layers, debris and trash in outlets, and damage to components are indicators of GR deterioration that can be identified during visual inspections.

An additional objective was to develop a visual guide, using a repository of photographs, for evaluating condition grades of GR components alongside the inspection sheets to limit the impact of subjective opinions during inspection. The guideline is based on inspections performed on the four GRs in Trondheim and should be updated as more GRs undergo inspections, including those in different climates. This iterative approach will help reduce uncertainties and improve the reliability and consistency of condition assessments.

Moreover, the study presented herein highlights the importance of considering issues and problems at various stages of the GR lifecycle, and the relation between design, construction and operational phase of GRs. For example, while blocked drainage systems can be identified and addressed during inspection and maintenance, design considerations should include factors such as sunlight exposure, inspection paths, wind preventive measures and adequate overlapping of protective layers, which may be traced back to the construction stage of the GR. Early identification of defects and potential failures can help prevent further deterioration or worsening of emerging issues.

Suggested further work includes developing a database that contains detailed condition states for each component and accessible information on available GRs and other GI installations to reduce the subjectivity of the proposed condition assessment guide. Establishing clear lines of communication with and between designated personnel responsible for the design, construction operation and maintenance of these systems is also suggested. These steps would greatly facilitate research, management, and expansion of GR initiatives, ultimately contributing to the achievement of the sustainability goals of the utility.

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