

Article

Climate Adaptation in Maintenance Operation and Management of Buildings

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Abstract: The aim of this paper is to analyze the basic criteria, trends, applications, and developments related to climate adaptation in building maintenance and operation management (MOM) practices in Norway. Investigations conducted as part of the study include an analysis of current literature addressing climate adaptation in relation to MOM practices, supplemented by a review of existing research projects and initiatives in this field. Three case studies involving different Norwegian building owner organizations were examined in order to investigate the current status of the application and extent of climate adaptation practices in relation to MOM. The study has revealed a significant gap between theory and practice when it comes to integrating MOM in relation to climate adaptation. The concept of climate adaptation is only addressed as a high-level strategic issue. The case studies thus emphasize the need for a structured process that can enable the incorporation of climate adaptation in current MOM practices. This proposes a generic and structured climate-adaptive MOM framework that will enable the incorporation of climate adaptation in into corporate MOM practices at different scales and organizational levels. Implementation of this flexible and transferable framework is expected to provide a basis for accruing further knowledge on climate adaptation. Further work with the framework should include the introduction of more tangible and tailored tools and processes, including checklists or scoring systems accompanied by relevant climate adaptation factors and plans.

Keywords: climate change; climate adaptation; buildings; maintenance; operation; management

1. Introduction

1.1. Background

It is clearly demonstrated that climate change is increasing the amount and intensity of precipitation in Norway, and that this will have a major impact on future built environments. As a result, we will probably have to make changes to the ways in which we construct, maintain, operate, and manage our buildings. According to the Intergovernmental Panel on Climate Change (IPCC) [1], an average increase of 20% in precipitation volumes has occurred over the last 100 years, and an additional 20% increase is expected before the year 2100. Moreover, projections for climate change in Norway [2] indicate that a warmer climate can be anticipated, accompanied by an increase in the frequency of extreme weather events and more intense precipitation in certain parts of the country. Changes in temperature will result in an increase in the number of freeze-thaw cycles, and a greater

proportion of winter precipitation will fall as rain. These changes will lead to greater demands to protect buildings from the effects of climate change.

Since Norway is already situated in a region characterized by relatively high levels of precipitation, moisture-related damage has always posed significant challenges to the Norwegian built environment. Current projections of climate change impacts indicate that these challenges will increase in the years to come. Moisture, damp building structures, and precipitation all combine to stress the building envelope (the facades and roofs) and can cause significant damage. Adapted and improved technical systems are required, and must be accompanied by comprehensive supervisory and maintenance regimes. Increased precipitation will also present challenges in terms of the floodwater threat, and factors such as drainage, water retention, and building-adjacent terrain considerations will become increasingly significant during the design phase of future buildings.

Approximately 80 percent of Norway's current buildings will be standing in the year 2050 [3], but not all of these are designed to meet the challenges resulting from progressive climate change [4] [5]. This fact underlines the importance of achieving a balance between mitigation and adaptation during the design of new, and the retrofitting of old, buildings. It also emphasizes that appropriate maintenance, operations, and management (MOM) strategies will be vital tools in ensuring adequate climate adaptation of Norway's existing building stock.

The adaptation of the built environment to climate change has received significant attention in Norway during the last two decades [6–8]. A prior study carried out within the framework of the Norwegian research program Klima 2050 [9] has recognized the need for research-based knowledge related to building maintenance [10]. The study identified a significant knowledge gap in the field of building maintenance and renovation, especially in relation to technical solutions and related components.

In 2014, Flyen et al. [11] recorded a significant time lag in the maintenance of Norwegian public buildings, arguing that this lag increases the vulnerability of the built environment to the stresses imposed by climate change. Furthermore, a national condition status report published by the Norwegian Consulting Engineers' Association [3] indicated that the entire built environment in Norway is worth approximately NOK 5800 billion, and that the cost of renovating this building stock to an adequate standard is estimated to be NOK 2800 billion. Even though this is the grand total for renovation due to all degradation aspects, climate related renovation needs can be argued to be substantial. To put this in perspective, the Norwegian gross national product (GNP) in 2016 was NOK 3100 billion [12]. Previous research has estimated that the total annual costs related to building repair in Norway are approximately EUR 1.65 billion [13].

1.2. Definitions

1.2.1. Climate Change

Climate change in the context of this article is defined as *“a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer”* [14]. Depending on which of the various IPCC scenarios we select, we can expect a global temperature increase of between 1.5 and more than 6 °C before 2100. In a Norwegian context, a temperature increase of between 2.3 and 4.6 °C is anticipated during the same period [2]. Future climate change will thus have a significant impact on the built environment. Estimates carried out on behalf of the Norwegian government show that the anticipated impact on the building and infrastructure sectors will be high both in terms of monetary and societal costs [15]. A conservative estimate indicates immediate costs of 0.1–0.2% of the GNP for the European countries. The estimate is uncertain and excludes, i.e., accumulated costs over time. If these accumulation effects are accounted for, the figure will be considerably higher [15].

1.2.2. Climate Adaptation

Two fundamental response approaches to climate change are recognized in the literature: climate mitigation and climate adaptation. Climate mitigation is defined by the IPCC [14] as *“the*

notion of limiting or controlling emissions of greenhouse gases so that the total accumulation is limited". The terminology used in this paper is based on definitions also provided by the IPCC, which define **adaptation** as *"the notion of making changes in the way we do things to respond to changes in climate"*. **Adaptation** in the context of climate change is defined by the United Nations as *"adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities"* [16]. The term **"climate adaptation costs"** is not within the scope of this paper.

1.2.3. Maintenance and Operation Management (MOM)

This paper presents work related to Maintenance and Operation Management (MOM). Terminology related to this term is based on definitions set out in the Norwegian industry standards NS 3424:2012 [17] and NS 3456:2010 [18]. Here, **maintenance** is defined as a *"combination of technical, administrative and managerial actions with the intention of maintaining or re-allocating the condition to a level that fulfils the functional requirements throughout the life-cycle of an item"* [17]. **Corrective maintenance** *"is maintenance carried out after fault detection and intended to put an item into a state in which it can perform a required function"* (EN 13306 [19]). **Preventive maintenance** is *"maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item"* (EN 13306). **Predictive maintenance** is condition-based *"maintenance carried out following a forecast derived from repeated analysis or known characteristics and evaluation of the significant parameters of the degradation of the item"* (EN 13306). **Operation** is a *"combination of all technical, administrative and managerial actions, other than maintenance actions, that result in the item being used"* [17]. **Upgrade** is related to *"work that is to be carried out on a building or its technical installations in such a manner that the building fulfils new, stricter demands and/or that the buildings' area or capacity of installations are increased"* [18].

The development of MOM strategies and the technical systems considered suitable for the implementation of said strategies are crucial to achieving appropriate climate adaptation of existing buildings to ensure that they meet future functional requirements. In this context, the term **functional** refers to *the expression of how the physical building works according to its purpose and fits the need of the user organization* [20].

1.3. Aims and Scope

The aims of this paper are firstly, to analyze the trends, applications, and development of climate adaptation as it applies to MOM practices; and secondly, to propose a climate-adaptive MOM framework for public and large building owners. It has the following objectives:

- to examine relevant and current literature addressing climate adaptation in MOM practices (Section 3),
- to review existing research projects in an attempt to understand the research landscape in this field in a Norwegian context (Section 3)
- to examine the application and extent of climate adaptation from a day-to-day MOM perspective (Section 4)
- to propose a generic framework that facilitates a structured process for developing climate-adaptive MOM practices for professional and public building owners that can reduce climate change risk and increase the resilience of the Norwegian built environment (Section 5).

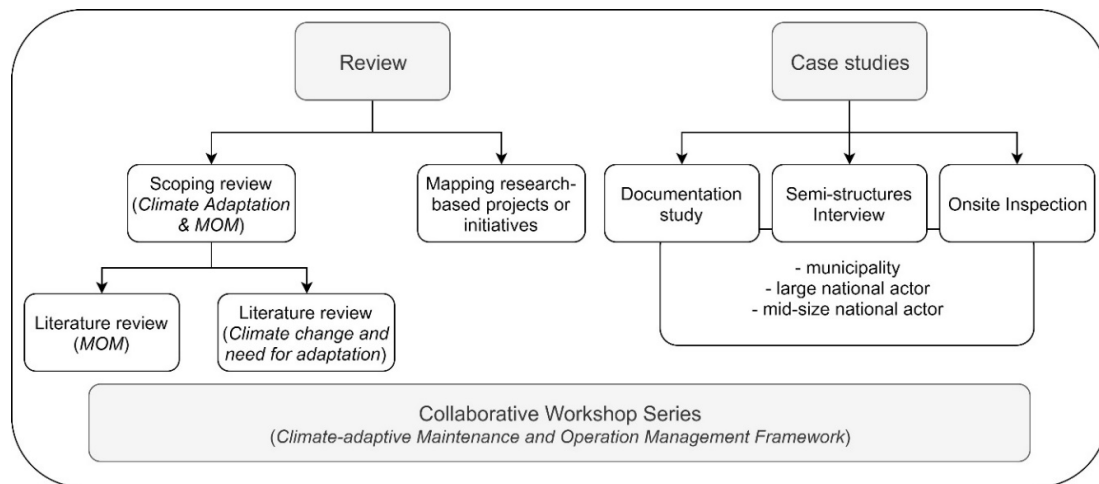
2. Methods

2.1. General Overview

A multimethod-based research approach is adopted here to ensure coordination and interdependency between Norwegian research efforts and everyday practice (see Table 1 and Figure 1).

Table 1. Overview of methods, objectives, and research questions.

Research Method	Scoping Review	Review of Norwegian Projects/Initiatives	Case Studies	Collaborative Workshop Series
Objective	1. To examine relevant and current literature addressing climate adaptation from a MOM perspective	2. To review existing research projects and understand the research landscape in this field	3. To examine the application and extent of climate adaptation from a day-to-day MOM perspective.	4. To propose a generic framework that facilitates a structured process for developing climate-adaptive MOM practices that can reduce climate change risk and increase the resilience of the Norwegian building environment
Research questions	1.1 What trends are emerging in current MOM-related literature?	2.1 What research-based initiatives or projects are associated with MOM and upgrade?	3.1 What are the characteristics of current MOM-systems for climate adaptation at different scales in Norwegian public sector institutions?	4.1 What should be added to or modified in terms of MOM practice in order to meet the challenges presented by climate change?
	1.2 What are the implications of climate change, and where is the need for climate adaptation?	2.2 What is the main purpose of the projects/initiatives?	3.2 What challenges do these systems face, and how can they be improved?	4.2 How should we structure a process for identifying climate-adaptive measures in MOM practices?

**Figure 1.** General overview and structure of the methodology.

2.2. Literature Review

An initial scoping review was carried out in order to examine the nature, extent and range of research activities that have addressed the incorporation of climate adaptation in MOM practice. The review was based in an established research methodology [21] by which the queries used to search the databases were taken from experts working on major research projects in the field, and based on the CIMO (context intervention mechanisms outcomes) framework [22]. The search string, keywords, and Boolean operators are shown in Table 2. Two electronic databases containing peer-reviewed literature were used; SCOPUS and Web of Science, which revealed 22 and 15 potentially relevant documents, respectively. However, based on their titles and abstracts alone, most of this literature was of little relevance to the scope of this paper. Nevertheless, we did identify some articles that discussed climate adaptation and MOM in contexts other than the building environment, such as civil engineering applications including railways, bridges, and road projects, or design stage applications. In addition to the initial search, a more traditional rapid review using the Google

Scholar search engine and the Science Direct database was carried out to identify trends in the field of MOM, climate change, and the need for adaptation.

Table 2. Keywords, Boolean operators, and search strings.

WHO	WHAT	HOW
<i>Intervention</i>	<i>Context</i>	<i>Outcomes/Mechanism</i>
Building	Climate adaptation	Maintenance
Architecture		Facility management
Construction		Operation management
		Upgrade
		Refurbishment
(TITLE-ABS-KEY (“climate adaptation”) AND TITLE-ABS-KEY (building OR architecture OR construction) AND TITLE-ABS-KEY (maintenance OR “facility management” OR “operation management” OR upgrade OR refurbishment)).		

2.3. Mapping of Research Projects and Initiatives

The main author has previously published a paper involving a literature study and a review of research projects involving Norwegian building owners in which MOM and upgrades were investigated [23]. An internal workshop was held to sort these projects into categories in matrix form according to their principal research theme and the type of decision-maker (main actor) involved.

The project review also involved dialogue with experts and major research project representatives in order to obtain an understanding of the current status of contemporary research. A draft of the project overview was also discussed with three major Norwegian building owners/managers and one of the largest construction consultant companies in Norway.

2.4. Case Studies

Three cases were selected to represent the building owner perspective. Selection was carried out to ensure representative variation in scale in terms of geographical location and climate exposure, building portfolio, and size.

1. Municipality. The municipality selected is one of the most highly populated in Norway. It maintains one million square meters of building stock, but is geographically categorized as a local actor with a relatively uniform level of climate exposure.
2. A large Norwegian actor. This actor is the largest owner of civil buildings in Norway. It owns a highly varied portfolio of more than 2300 buildings covering more than 2.8 million square meters. The buildings are distributed across the entire country and their levels of exposure to climate stresses vary according to location.
3. A medium-sized Norwegian actor. This actor was selected in order to offer insights into a smaller organization with a limited, though geographically widespread, portfolio of buildings. The actor manages 45 airports of varying size.

Three principal methods were adopted for this investigation and were applied according to the guidelines presented by Yin [24] as follows:

- (a) Documentation study. An initial examination of specific MOM components was carried out based on a documentation study. This included a review of drawings, operational plans and condition state analyses as set out in guidelines developed by Weber [25]. The number of case-specific documents examined is presented in Figure 2.
- (b) On-site inspection. A single on-site inspection for each of the actors was carried out by two of the authors of this paper. During the inspection, they were accompanied by a maintenance officer who commented on maintenance needs and the extent to which different solutions were working. The main objects of analysis in this case were the building envelope and adjacent

terrain, with a specific focus on identifying climate related damage and areas of weakness of the building envelopes.

- (c) Semi-structured interviews. Methods (a) and (b) were supplemented with semi-structured interviews (Yin [24]) with representatives from the municipality (operations officer, project manager, and maintenance and sustainability advisor), the large Norwegian actor (senior project managers, innovation officers, building workers, and administrative personnel) and the medium-sized Norwegian actor (maintenance officer). The interviews were also used to extend the results from the on-site inspection of one building to a more general perspective in order to provide a more generic representation of the MOM procedures of each actor.

Case studies			
	Municipality	Large national actor	Mid-size national actor
Documentation study	21	25	11
Onsite Inspection	1	1	1
Semi-structured Interview	3	10	1

Figure 2. Numbers of case-specific documents examined as part of the case studies.

2.5. Joint Workshop Series

A series of joint workshops involving experts in the fields of building engineering and climate adaptation were carried out in order to develop a climate-adaptive MOM framework. The knowledge gap that emerged as a result of the literature review, combined with an identified need to incorporate climate adaptation in MOM practices based on examination of the case studies, served as the starting point for preparation of the proposed framework. The workshop also established a set of four requirements that the framework would have to meet:

- Compliance with the Norwegian standard EN 15331—“Criteria for design, management, and control of maintenance services for buildings” [26].
- Compliance with the ISO 9001 standard “Quality Management Systems—Requirements” [27], which states that “Management of the processes and the system as a whole can be achieved using the PDCA (PDCA stands for Plan-Do-Check-Act) cycle with an overall focus on risk-based thinking aimed at taking advantage of opportunities and preventing undesirable results”. Concepts set out by the IPCC [1] regarding risk assessment are also adopted in this context.
- The framework should be generic and thus applicable at all scales and for all actors carrying out maintenance and operation management on buildings and other facilities.
- The framework should be specifically applicable in a Norwegian context. The findings from various projects linked to the Klima 2050 research centre [9], as well as the report “Climate in Norway 2100” [28], were taken into account.

3. Review of Literature And Initiatives

3.1. Scientific Literature Review

Climate change is forcing society to address factors affecting building maintenance needs from a life cycle perspective. This includes the use of proactive maintenance to extend the operational life of buildings and equipment. A key to this proactive approach is the search for smart and innovative MOM assessment tools.

The ISO standard “15686-8:2012—Life Cycle Planning: Reference service life and service-life estimation” [29] defines the so-called “factor method” for the estimation of the expected service life of

a component or assembly under the influence of a well-defined set of conditions. The method addresses a number of different factors: (i) material (properties), (ii) design (details), (iii) execution (on-site factors), (iv) climate stresses, such as rain, wind, snow, and chemicals, and (v) maintenance (preventive measures). The first three factors address resilience in the face of deterioration. The fourth influences the speed of deterioration and the fifth addresses measures designed to extend service life. All of these factors are important and should be taken into consideration from the beginning of the design process to project completion, not least as a means of ensuring the incorporation of life cycle planning (LCP). Further development of the standard should include need assessments for the technical and functional upgrade of buildings. New standards are currently in preparation (e.g., CEN TC50, WG8) that address topics within the field of so-called sustainable refurbishment.

Maintenance and operation management takes place during the operational life of a building. Construction projects related to this phase of a building's lifetime have been the subject of increased interest from project management researchers in recent years. In Norway, for example, the research project OSCAR (<http://www.oscarvalue.no/>) is actively seeking to identify methods for the optimization of building projects, with the primary aim of contributing to value creation and capture in the interests of owners and users during the building life cycle.

An understanding of the role of facility management (FM) and MOM is crucial to ensure the sustainable extension of building lifetimes, and it is essential that proper emphasis is given during the early planning phase. Recent research in Norwegian contexts indicates that qualitative early-phase planning will assist in meeting sustainability requirements and contribute towards ensuring more secure financial conditions for refurbishment projects [30]. Initiatives such as OSCAR rely heavily on the insights of Cooke-Davies [31]. In recent years, such insights have been applied under Norwegian conditions by Hjelmbrække et al. [32], and studies such as this have helped to illustrate the challenges encountered in the Norwegian construction sector. Hjelmbrække et al. [32] have proposed a model for the inclusion of strategic perspectives during the operational phase of construction projects. The core insight shared by the foregoing authors is that building-related operations, and maintenance strategies in particular, must be considered during the planning of new projects. In the absence of a proper knowledge of the actual practices that a typical maintenance scheme may involve, any alignment of project execution with the uoperational phase may be highly problematic.

Fregonara et al. [33] proposed a multidisciplinary approach to decision-making in this context taking into account the property market, project economics, architectural technology and building physics, life cycle costing methodologies and energy consumption analyses. Kamari et al. [34] have presented a comprehensive sustainability framework for the development, assessment, and auditing of building renovation performance. Key components in this model include the support given to decision-makers during the project's lifecycle and the need to address the sustainability of entire renovation projects, including the introduction of new categories, criteria, and indicators.

The financial consequences of climate change have been identified by the statistical analysts Finance Norway, showing a 30% increase in insurance claims payments during the last five years [35]. The need for well-functioning strategies and technical systems to protect the building envelope and other components has also been demonstrated in references [36,37]. An examination by the present authors of the building defects archive held by SINTEF Building and Infrastructure reveals that damage to, and defects in, existing Norwegian building stock can be explained as follows:

- 75% of investigated defects are caused by moisture
- 67% of investigated defects are related to building envelopes
- 25% of investigated defects are caused by precipitation
- 33% of investigated defects linked to exterior walls above the terrain surface are caused by moisture
- 50% of investigated defects linked to roofs and terraces are caused by moisture.

The most critical aspects of climate change that are relevant to future building adaptation are increases in annual mean temperatures and levels of precipitation, increasing volumes of winter precipitation falling as rain, and increases in the wind-driven rain component. An increase in the

frequency of freeze–thaw cycles (temperature oscillation around 0 °C) is also anticipated in the future [4]. Other factors such as the higher frequency of events such as avalanches, floods, and storm surges, combined with rising sea levels, are not considered relevant to this study, and are not discussed further.

This study has identified four major climate change factors. These are summarized in Table 3, together with a list of the key technical challenges associated with them.

Table 3. Climate change factors and associated technical challenges. This table has previously been presented in Grynning et al. [38].

1. Increase in Annual Temperatures	2. Increase in Precipitation (Rain)	3. Winter Precipitation as Rain	4. Driving Rain
Increased mould growth potential	Increased mould growth potential	Increased structural loads	Increased mould growth potential
Increased rot decay risk	Increased rot decay risk	Stress on roofing robustness	Increased rot decay risk
Greater frost-cycle variation	Longer periods of free-standing water on roofs	Increased water pressure on ground constructions	Need to upgrade surface treatment of facades
Reduced heating demand	Stress on the robustness of roof membranes	Ice formation on surfaces and in pore structures of materials	Drying out of walls
Increased cooling demand	Freeze–thaw cycles		Flashing details
	Stresses on membrane joints		Need to identify better window/door mounting solutions
	Gaskets and protrusions		
	Drain/gutter capacities		
	Blocking of drains		
	Overflow in drains		
	Standing water due to limited drain capacity		

One can see from the challenges listed above that the design of the building envelope is key to the climate adaptation of buildings. Adaptation is a general term that denotes a building’s physical properties and its flexibility to adjust to changes in use, function and size [20]. Increases in temperature will promote mould growth within building envelopes. A study carried out by Almås et al. [13] has shown that an estimated 615,000 buildings in Norway are located in areas with a potentially high risk for rot decay. In 2100, this number is anticipated to rise to 2.4 million. Increased temperatures will also result in a general decline in demand for heating and corresponding increases in cooling demand.

3.2. Review of Research Projects and Initiatives

Table 4 provides a summary of research projects identified as being useful to this study, categorized in matrix form according to main actor and research theme. A total of 28 projects are listed, and ten of these address climate adaptation issues. The reviews of existing literature and relevant research projects conducted as part of this study have revealed a number of thematic research needs. One of the general findings is that the research projects relevant to MOM and building upgrades exhibit a notable bias towards energy efficiency in buildings. A more detailed description of these projects is presented in a previous study by the present authors [23].

Table 4. Summary of research projects identified as being useful to this study, categorized in matrix form according to main actor and research theme. Green shading indicates cases where the topic in question is considered highly-researched. Red shading indicates that the topic has been the subject of little or no research.

Level	Main Actor of Interest	Research Theme		
		1. Climate Adaptation	2. Energy Efficiency	3. Economy
A. Law and legislative	Ministry/Directorate	[13,39–42]	[43–47]	[47–49]
B. Legislative/planning/strategy	Municipality/local authority	[13,39–42,50,51–59]	[43–46,57,58,60,61]	[62]
C. Strategy/system	Managers/MOM operators	[24,51–56,63]	[43–46,60,64–77]	[62,78–80]
D. System/solution	Consultant/contractor	[13,81,82]	[13,43–46,64–66,69,70,75–77,82–85,86]	[62,87,88]
E. Solution/component	Product manufacturer		[13,43–46,82]	

3.3. Knowledge Gap

Due to anticipated changes in climate, building envelopes will be subjected to increasing levels of stress in the years to come. Our research review demonstrates that projects addressing the climate adaptation of buildings using MOM focus mostly on the effects of moisture and resilience to potential moisture-related problems. This is mainly due to a broad understanding that future increases in precipitation, combined with annual average increases in temperature, will become the greatest sources of stress on the building envelope in the future. These impacts may reduce the lifetimes of individual building components and increase overall damage risk, and underline the importance of promoting appropriate maintenance strategies and schedules.

Implementation of climate adaptation measures for buildings has been on the agenda in Norway for some years, but the climate adaptation of buildings involving MOM has received very little attention from the research community, and Grynning et al. [23] have identified key knowledge gaps in this field. This study has also been able to identify a need to provide an account of what MOM practices entail and to develop a framework for industry application.

Hauge et al. [89] found that numerous user guides exist to prepare societies for the coming climate challenges, but none of the user guides describes decision processes in depth, and target groups are not specified. Stagrund et al. [90] found little research on the consequences of climate change on buildings in cold regions. The majority of the identified literature concerns climate change impacts on buildings in warm climates, with overheating being seen as the greatest challenge.

Hauge et al. [91] have studied barriers and drivers for climate adaptation in Norway. They conclude that pursuing changes across the practical, political, and personal spheres is essential.

4. Case Studies

4.1. General Remarks

The three organizations introduced in Section 2.4 have all stated that climate adaptation is an explicit ambition as part of their corporate strategies. However, the levels of detailed planning and, perhaps also, of commitment to this ambition vary somewhat. It is clear that there exists wide

variation in facility management strategies and implementation within these organizations—ranging from incident-based corrective maintenance programs to long-term preventive plans and strategies.

4.2. The Municipality

The MOM strategies employed by the municipality revolve around a five-year cycle, as shown in Table 5. Every fifth year an extensive condition status analysis is carried out by an external consultant. This analysis forms the basis for longer term MOM plans addressing the needs of the building envelope, technical installations (heating, cooling, ventilation, etc.) and interior MOM and building upgrade needs. On this basis, the municipality prepares annual MOM plans and reporting procedures. This structured approach to planning ensures adequate levels of supervision of day-to-day maintenance and upgrade needs. It also helps in the facilitation of longer term planning.

Dedicated maintenance officers are responsible for the day-to-day maintenance and operation of municipal buildings. As a rule, a maintenance officer may have responsibility for one or several buildings, depending on the size of the structures in question. External contractors are brought in if major MOM or upgrade tasks have to be carried out.

A set of annual MOM procedures is provided to responsible maintenance officers, consisting of a booklet describing all the detailed procedures and mandatory checks that must be carried out during the year in question. An ongoing series of checklists is completed as the year progresses. At the end of the year, each officer submits his or her booklet to the municipality's central property department. Booklets are laid out in nine operational chapters as follows (taken from the 2013 edition): 1. A description of tasks with checklists. 2. A checklist for mandatory tasks. 3. A checklist for critical operational tasks. 4. A checklist for (less critical) operational tasks. 5. A checklist for electrical systems and equipment. 6. A checklist for outdoor areas (e.g., municipal playgrounds). 7. Internal building safety checks. 8. MOM procedures for bomb shelters. 9. Internal checks of operational tasks.

The procedures and systems descriptions in the booklets are for the most part in paper format, making revisions cumbersome. It was also found that much of the knowledge in the organization is tacit and linked to the know-how of experienced individuals, making the organization vulnerable to changes in personnel. Such practices may impair organizational knowledge transfer on a broader scale.

In order to assist the organization in the further development of its systems, we recommend that greater focus should be directed on the digitalization of tools (e.g., using Building information modeling (BIM)), communication, and processes. This may help to promote proactive knowledge sharing at all levels in the organization. Moreover, higher levels of digitalization may promote the transfer of knowledge from individuals into a structured organizational knowledge base.

Table 5 presents a summary of the overall MOM strategy exercised by the organization. The review of documents carried out for this case study indicate that specific challenges exist linked to a lack of climate change planning, and a failure to implement climate adaptation initiatives. For example, the present authors are skeptical of the resilience of some technical systems to increased levels of precipitation, and no strategy exists for the upgrade of these systems.

Table 5. Stepwise procedure for the management of MOM needs and tasks as exercised by the municipality in this case study.

Step 1— Maintenance Needs	Step 2—Long-Term Planning	Step 3—Annual Plans and Work Orders	Step 4—Revision of Plans
Task:	Task:	Task:	Task:
Assess building condition Define long-term maintenance needs	Prepare 5-year maintenance plans Adjustment of maintenance needs and transfer to budgets	Year on year MOM procedure for building maintenance officers	Revise annual plans and booklets including checklists and tasks
Persons responsible External consultant and internal administrators	Persons responsible Building and head administrators	Persons responsible Administrator and building maintenance officer	Person responsible Building maintenance officer
Actions: Condition status analysis of buildings Prepare long-term plans (also for funding purposes)	Actions: Coordination of maintenance and potential upgrade needs	Actions: Prepare checklists for the maintenance procedure booklets	Actions: Submission of plans/booklets to central property department at year end

4.3. The Large Norwegian Actor

Climate adaptation was introduced as an area of focus in this property owner's strategy in 2014 [92]. Currently, the organization's focus is at a more strategic level—*"climate adaptation shall be accounted for in the light of climate changes"*. This statement corresponds with the findings resulting from our research project review that the majority of current research is limited to high-level strategy applications. This actor currently includes no operational plans or specific proposals regarding strategic implementation, which underlines the need to develop a knowledge framework within organizations in general to enable them to implement climate adaptation measures in practice. Of the three case study organizations, this actor possessed the most comprehensive facilities management (FM) system. However, we recognize a need to introduce actions to strengthen the organization's climate adaptation implementation strategy. The existing climate adaptation system for buildings adheres to a structure similar to that described by Cooke-Davies [31], which accentuates the need to establish strong links between the operations and project management levels within the organization in order to meet corporate strategies and goals. The facility management system and tasks are assembled in a database tool and adhere to a stepwise procedure as shown in Table 6. The tool collects all technical and practical information regarding the owners' properties. The property maintenance officers have overall responsibility for entering maintenance needs in the tool. Building administrators register the entries and transfer these to short- and mid-term maintenance plans and budgets. The tool can then be accessed by maintenance officers to obtain activities and work orders. "Long-term" in the context of this organization is a period of five years.

Table 6. Stepwise procedure for the management of MOM needs and tasks as exercised by the large Norwegian actor in this case study.

Step 1— Maintenance Needs	Step 2—Long-Term Plans	Step 3—Annual Plans	Step 4—Activities and Follow-Up
Task:	Task:	Task:	Task:
Definition of maintenance needs	Define 5-year maintenance plans Adjustment of maintenance needs and transfer to budgets On budget approval, needs are transferred to annual plans	Access annual action budgets and preparation of work orders	Implement work orders
Persons responsible	Persons responsible	Persons responsible	Persons responsible
Maintenance officers or administrators	Building and head administrators	Building administrator	Maintenance officer
Actions:	Actions:	Actions:	Actions:
Register needs Transfer to long-term plans	Edit action and budget approval Periodization of actions	Edit action Prepare work orders Closing of actions	Edit work orders Prepare orders for external assistance Closing of work orders

The authors have identified some challenges related to the implementation of the system for this case study. For example, defects in building envelopes that have resulted in ongoing water leakages were revealed during the on-site inspection and in interviews, underlining the importance of strengthening the links between operations and management levels within the organization.

Secondly, the level of detail inherent in the management tool could be improved. Critical building components should be the subject of greater attention from a climate adaptation perspective. Maintenance intervals for such components should be introduced and adapted to local, site-specific, needs.

Finally, building damage and critical events caused by “extreme weather” incidents may be avoided by implementing early warning and weather forecasting systems. The need for such systems was underlined by a flooding incident in a building adjacent to one of the actor’s properties. This incident emphasizes the need for greater cross-organizational communication, as well as a need to consolidate internal corporate strategies and plans.

4.4. The Medium-Sized Norwegian Actor

The building considered in this case study is located in an airport for domestic and international flights. This actor’s maintenance department employs five maintenance officers and a maintenance manager, who is responsible for day-to-day task planning. The department is responsible for maintenance across the entire airport, including the building considered in this study. The actor uses an interactive management tool for day-to-day building management. The users of the building report their needs to the maintenance department, which in turn plans and coordinates a daily schedule. Recurring maintenance tasks are also plotted in the system, enabling the department to plan and prioritize its assignments according to criticality and urgency. We observed no long-term planning integrated into the MOM system. Instead, it was the task of the maintenance manager to report annual funding needs based on the condition of the building. In contrast to the two previous case studies, no strategic planning structure exists for this actor. We recommend that this situation be remedied.

This actor's management system makes it easy for building managers to keep track of the maintenance needs at any given time. The aim here is to ensure that functional failures can be rectified quickly, enabling building managers and the operations department to prioritize issues based on critical need.

However, we recognize that it would be beneficial if the management system also incorporated a comprehensive and long-term maintenance and upgrade plan based on condition status analyses and the estimated lifetimes of key components and products. The development of a more long-term approach to the management of building stock may make a useful contribution towards major maintenance and upgrade planning, and at the same time facilitate long-term expenditure budgeting. This would provide a detailed overview of future maintenance tasks and enable potential synergies in situations where two or more major improvements could be carried out at the same time with adequate quality and at lower cost.

Periodic tasks such as the supervision of technical installations are guided by procedures. Needs and corresponding tasks are reported on a continuous basis. However, the lack of a structured long-term plan for MOM tasks presents a challenge. In an interview carried out with the operator, it emerged that aspects of the main terminal roof could be used to illustrate this issue. The roof was installed in 1986 and had been subject to considerable wear and tear. However, since no leaks had been detected, no funds had been assigned for a thorough condition status analysis or replacement, even though the roof's expected lifetime was close to expiry. This approach flies in the face common sense that dictates that waiting for a component to fail before initiating a response will lead to additional work as a result of consequential damage.

5. A Climate-Adaptive Maintenance and Operation Management (MOM) Framework

5.1. Definitions

The term climate-adapted buildings and building structures is commonly applied to structures that are planned, designed and built to withstand various types of external climatic stresses including precipitation, snow deposition, wind, temperature, storm water and exposure to the sun. However, adaptation to a changing climate must also incorporate reductions in the risks to wider society. It is not sufficient simply to restrict our focus to historical weather data when designing and maintaining buildings [93].

Climate-adaptive maintenance is hereby defined for the purposes of this study as the combination of technical, administrative, and managerial actions carried out with the intention of maintaining, allocating, and adjusting the condition of an item to a level that fulfils the functional requirements throughout the life-cycle of the item in response to actual or expected climatic stimuli.

Climate-adaptive maintenance and operation management is hereby defined as a combination of all technical, administrative, and managerial actions, including maintenance actions, that result in the item being used and maintained in response to actual or expected climatic stimuli.

5.2. A Climate-Adaptive Maintenance and Operation Management (MOM) Framework Workflow

Figure 3 illustrates the climate-adaptive MOM framework workflow that is proposed in this paper. Climate adaptation exerts most influence during the planning and decision-making stages of the planning phase. For this reason, the workflow focuses primarily on the planning stage of the PDCA cycle since this is intended only to account for the climate change aspect. The components of the workflow are discussed in detail in the following.

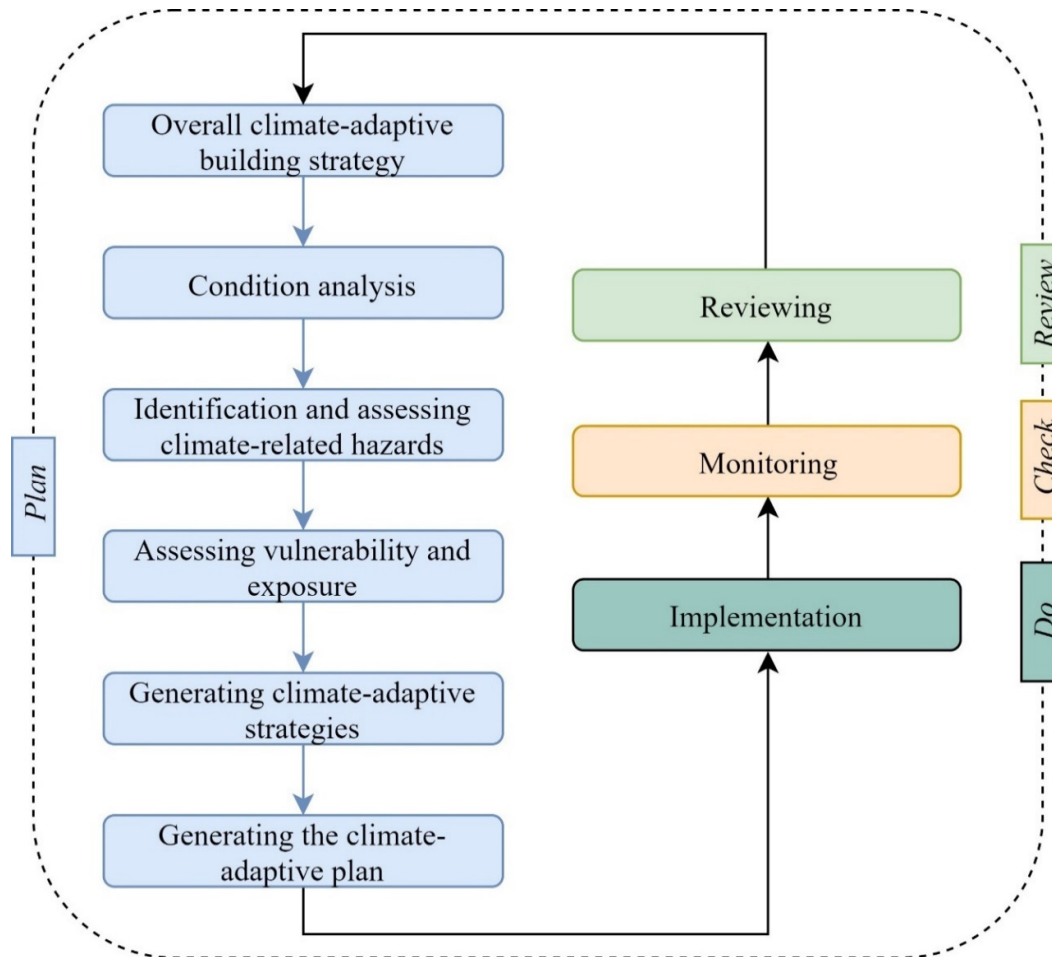


Figure 3. Proposed climate-adaptive maintenance and operation management (MOM) workflow.

Overall climate-adaptive building strategy: This step is designed to determine the applicable climate-related service and performance specification for the building asset in question in compliance with the EN 15331 standard [26]. It will also include a strategy to safeguard property value in the face of exposure to climate change. The step shall be reviewed at specified regular intervals and in situations where a major change in performance requirements is required in response to new knowledge.

Condition analysis: This step is designed to determine the condition of the building asset in relation to a given reference level (performance requirement). The reference level will be set out in a climate-adaptive building strategy. The data required to carry out a risk analysis shall be collected, and the analysis performed according to guidelines set out in the Norwegian standard NS 3424.E:2012[17].

Identification and assessment of climate-related hazards: This step is designed to identify potential hazards to the building asset in question, and impacts in response to actual or expected climatic stimuli in a Norwegian context. To support this step, Table 7 provides a structured overview of hazards that may be anticipated in a Norwegian context as a result of climate change and their expected impacts on the building asset.

Table 7. Overview of potential hazards in response to anticipated climatic stimuli and their implications. Red shading indicates a high degree of influence and white very low or no influence.

		Hazards							
		Increased precipitation				Increased temperature	Sea level rise	Flooding	Freeze–thaw cycles
Implications	Wind-driven rain	Accumulative precipitation	Wet winter precipitation	Torrential precipitation					
		Mould growth	Red	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
	Rot decay	Red	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
	Biological growth	Red	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
	Moisture creep	Orange	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
	Other fungi	Red	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
	Structural overload	Orange	Red	Red	Yellow	Red	Red	Orange	Orange
	Heating/cooling demand				Red				
	Outages/downtime					Orange	Red		
	Cracks	Orange	Yellow	Yellow	Orange	Yellow	Orange	Red	Red
	Spalling	Orange	Yellow	Yellow	Yellow	Yellow	Orange	Red	Red
	Groundwater pressure	Yellow	Orange	Orange			Red		
	Corrosion and/or carbonation	Yellow	Yellow	Yellow	Yellow	Yellow			
	Blocking of drains	Yellow	Orange	Red	White	Orange	Red	Orange	Orange

Assessing vulnerability and exposure: This step is designed use the data and knowledge gathered during previous steps to assess the vulnerability and capacity of the exposed building assets in response to identified hazards.

Assessing climate-related risk: This step is designed to identify, assess and prioritize the risks resulting from actual or anticipated climatic stimuli. A graphical risk matrix is constructed illustrating probabilities and consequences. A priority list shall be drawn up to categorize and rank risks based on the level of response required (from immediate to no action).

Generating climate-adaptive strategies: This step is designed to generate and evaluate climate-adaptive strategies in response to identified risks. Strategies may be generated by following the structured matrix proposed in this paper that recommends strategy categorization based on (a) maintenance type (corrective, preventive or predictive) and (b) the risk factor(s) that require mitigation (hazard, exposure, and vulnerability). For example, a hypothetical case study involves a flat roof showing no signs of leakages (see Table 8). The roof is then exposed to levels of precipitation and increased temperatures that were not built in during the design stage. The strategy categorization

provides a detailed overview of potential impact in terms of risk reduction and enables identification of the most useful strategy for a given building asset. This approach may prove to be beneficial to actors with responsibility for the management of large building asset portfolios, within which buildings or building stock may require component-specific adaptations to changing climate stimuli and consequent exposure risk.

Table 8. Matrix showing the climate-adaptive strategy proposed in this paper. A (potentially) leaking flat roof is taken as an illustrative example.

Maintenance Type	Hazard	Exposure	Vulnerability
Corrective	Fast cleaning (carry water in buckets)	Change roof covering when damaged	Not applicable
Preventive	Increase dimensions of roof guttering and drainage system	Change roof covering before end of expected service life	Training of MOM personnel
Predictive	Sensor system warning	Change roof covering when embedded sensor alerts that service life is about to end	Direct weather forecast warning to all involved stakeholders

Generating climate-adaptive plan: This step is designed to facilitate the preparation of an adaptation plan and strategy document that incorporates the main findings of previous steps, and which provides clear direction for implementation and long-term execution.

Implementation: This step involves implementation and execution of the climate-adaptation plan generated in the previous step.

Monitoring: This step is designed to facilitate monitoring and performance measurement of the climate adaptation plan and the effectiveness of its risk mitigation measures. Performance is rated with reference to the objectives, requirements and planned activities identified in the strategy set out for the building asset in question.

Reviewing: This step is designed to review the adopted climate adaptation strategy and plan based on the monitoring and performance indicators emerging from the previous step. Risk assessments and strategies may be upgraded based on the findings of the review process and subsequently implemented in new plans.

6. Conclusions and Further Work

This study has adopted a multimethod research approach to the analysis of the basic criteria, trends, applications, and developments related to climate adaptation in connection with building maintenance and operation management (MOM) practices in Norway. The study concludes that there exists a significant knowledge gap between current maintenance and operation management practice and the strategies that are required to safeguard adequate adaptation to climate change. The study recommends that future research should focus on resolving this gap by addressing the two factors in combination. A review of practices and research projects has shown that climate adaptation is considered only as a high-level strategic issue in many organizations and that there is a need to incorporate the concept at lower organizational levels. An analysis of the three case studies has served to emphasize the need to adopt a systematic approach to the integration of climate adaptation considerations in current MOM practice.

This study proposes the adoption of a climate-adaptive maintenance and operation management framework. The framework involves a generic and structured process that facilitates the incorporation of climate adaptation in MOM practices on different scales and at different organizational levels. It is anticipated that implementation of this flexible and transferable framework will provide a basis for acquiring more knowledge on the topic of climate adaptation. Further development of the framework should include the introduction into organizations of more tangible

and tailored tools and processes, including checklists or scoring systems accompanied by relevant climate adaptation factors and plans.

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