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RESEARCH ARTICLE

Quantifying the impact of inadequate building management and maintenance on damage, failures and functional defects

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Abstract
Damage, failures, and defects in buildings create an enormous cost for stakeholders. This study examined technical aspects of inadequate management and maintenance causing moisture and indoor environment related damage instances. Using a dataset of 2100 diagnosed causes of damage based on real damage investigations carried out in Sweden, several of the factors causing damage were identified. The collected causes of damage in the dataset were cross-compared to several parameters and variables. Almost one-fourth of all building damage resulted from inadequate management and maintenance, with 87% of these cases being the responsibility of property owners or their trustees. In total, 38% of the management and maintenance-related damage was found to be associated with building services systems, such as inadequate stormwater treatment or defective ventilation. Furthermore, a high proportion of damage (20%) was attributed to an exceeded technical service life, particularly in roofing and terrace membranes, walls, and doors. Rain and snow were the most common sources causing damage in the management phase. A high portion of the causes of damage were on an elementary level and should be easily avoidable, such as insufficient cleaning of ventilation pipes and gutters, or worn-out building components where the technical service life was exceeded. Based on the results, a list of recommendations for preventive actions was made.

Keywords Building failures · Building maintenance · Building management · Building damage

1 Introduction

1.1 Background

Damage, failures, and functional defects in buildings create high costs for society and stakeholders. Losses due to the inefficient use of resources and direct and indirect costs for repairs of damage, failures, and functional defects in Sweden were estimated to be between 5.9 and 7.3 billion euros in 2016, which corresponds to over 1% of Sweden's Gross National Product, GNP [1–4]. Approximately 70% of those costs were attributed to free water leakages, moisture, mold, or other indoor environmental problems [1, 5]. Such kinds of damage are universal and have been reported in other countries [5–23]. To facilitate the reading of this paper, if not specified in detail, damage, failures, or functional defects are henceforth referred to as damage.

A literature review carried out by Mundt-Petersen et al. [12], consisting of national and international studies, investigations and different kinds of surveys, concludes that there are a large number of relevant studies focusing on the cost aspect of damage [1, 13–23]. Although, it might be known that inadequate maintenance cause damage, almost all reviewed studies ignore the management phase [12]. Reviewed studies primarily focus on the construction phase, but some also partly include the design phase [1, 5, 8, 14–17, 20, 22–28]. Except for some suitable studies [25, 29–46] and proper national initiatives systematically collecting data

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[9, 47–53], there is a general lack of technical aspects, especially studies including detailed technical information about damage and causes of damage, considered in the reviewed studies [12].

Although almost 50% of all causes of damage, failures, and functional defects occur during the management and maintenance phase, including renovation and rebuilding [29], there is a general lack of studies investigating the causes of damage derived from this stage, except for a few studies [12, 29, 38, 39]. Sassu and De Falco [39] studied damage from lawsuits, including a comparison of the number of damage occurrences in the design, construction, and maintenance phases, and noticed a similar percentage of damage caused by maintenance as Mundt-Petersen [29]. In contrast, Chong and Low [38] only found a limited amount of damage occurrences caused by inadequate maintenance. Some other studies partly deal with damage found in the maintenance phase but derived from previous stages, such as how cost from poor quality is transferred to building operation and maintenance [18], maintenance issues caused by poor or inadequate design [37], and methods to manage defects in building maintenance [54].

Moreover, Mundt-Petersen [12] noticed several studies which exclude technical aspects and explain and attribute failures or the cause of the damage to human-related errors in qualitative or general terms, such as bad motivation, lack of knowledge, insufficient information, stress, financial issues, inadequate use of resources, and inadequate systems or structures [1, 5, 6, 11, 13–17, 20, 21, 23, 26–28, 55–57]. Only a few studies discuss which actor is responsible for the cause of different damage [12, 14, 22, 29]. Love and Josephson [14] reported that the actors who cause a need for repair or rework tend to blame others for their failures. Porteous [57] recommends not pointing out the actor who may be responsible for the damage, as this does not improve building processes and quality. In these former works, technical aspects remain understudied, hindering accurate diagnosis of damage and remediation actions to reduce the incidence of damage occurrences linked to inadequate maintenance.

Until now, there have been only limited studies including statistics of damage in buildings in Sweden [1, 7–10, 58]. The reasons behind the research gaps are likely linked to the inaccessibility of damage data, which is usually owned by private actors who do not make the information public due to the risk of a bad reputation and lost capital of trust [1, 5, 8, 59]. Due to the lack of damage-specific data based on real damage investigations, several studies relied on expert workshops or were conducted through questionnaires and interviews [1, 5, 8, 10, 12, 19, 25–28, 38, 55, 60, 61] as well as case studies [12, 14, 15, 22, 23]. Unfortunately, some results from studies carried out as questionnaires and interviews [1, 10] seem to deviate from studies based on data from damage investigations [8, 12, 29, 62, 63].

No studies using a completely randomized sample were found. This may, for example, depend on whether the damage was not documented because it was not covered by insurance, or if no professional investigation was undertaken since the damage was repaired by the property owners. However, there are some large datasets that, given their specific areas and limitations, might be viewed as being close to randomized [40–42, 44–46, 61, 64]. For example, Van Den Bossche et al. [40] and De Vos et al. [41] present the number of damage occurrences linked to technical aspects based on 27,074 cases handled in court. Carretero-Ayuso et al. [44–46] also investigate damage and technical aspects cause damage instances in Spanish building using multivariate methods from cases handled in court. Holme et al. [61] and Bechner et al. [64] have investigated damage in Norwegian houses and presented valuable quantitative information about the design of the studied buildings, as well as the location and indication of mold damage observed.

1.2 Aim

This study aims to identify, evaluate, and analyze the causes of damage that occurred during the maintenance phase. Based on that, the study proposes recommendations for preventive measures to reduce the number of damage occurrences.

1.3 Limitations

This study focuses on the causes of damage that occur during the maintenance phase. Hence, causes of damage that occur in the design or construction phase, including inadequate design or construction in renovation, were not the focus of this study. This means that the causes of damage in this study could not be attributed to inadequate design or incorrect construction, nor was it a new building or caused during renovation. Damage and causes of damage, which were noticed and successfully repaired during the construction phase before the building was handed over to the property owner, were also excluded from this study.

The study is limited to the technical aspects of why damage occurs. This means that human-related issues and qualitative aspects, such as lack of motivation and time pressure, are not included in this study. Furthermore, no economic aspects are considered, and one damage is viewed as equal in the sample, independent of repair costs.

The study is based on quantitative data from real-world damage investigations on moisture and indoor environment issues collected in a dataset according to the method as presented below. In agreement with similar studies the dataset is not randomized since this is very difficult, if even possible, in practice. The sample in the dataset consists of buildings where damage was reported and investigated in Swedish climate conditions. The damage is assessed in accordance with Swedish laws, rules, and regulations [65, 66].

2 Definitions

Depending on the purpose of the study, available data, initial conditions, and current laws and regulations in different countries, the definitions of damage are slightly different. The differences in definitions mean that comparing definitions, parameters, and variables describing different technical aspects from different studies should be cautiously done.

In this study, previously presented definitions by Mundt-Petersen et al. [29], Mundt-Petersen et al. [67], and Wallentén et al. [62] are used as given below:

- A damage occurrence is defined as when a material or building component has lost its essential properties, such as strength, or by the release of harmful or disturbing emissions due to either chemical imbalance or microbial growth, which may create, among other things, unwanted odors, discomfort, Sick Building Syndrome (SBS), and Building Related Illness (BRI). The definition corresponding to the meaning of "damage" is in standard ISO 22185-1:2021 [68].
- A failure is defined as an apparent deviation from proper procedures, or if an obvious risk was taken that may lead to future damage.
- A functional defect is defined as not fulfilling needed feature requirements, such as when inadequate ventilation results in an accumulation of disturbing emissions, odor, or other discomforts.

The parameters used in this study to describe damage, and its causes are shown in Fig. 1. Each parameter is described by a value, referred to here as a variable. For example, the parameter *building component* has the value (variable) *roofing membrane*, as shown in the example in Fig. 1. It is essential to distinguish between the damage itself, which may occur in a building material or a building component, and the cause of that damage that creates the actual damage. The specific cause of damage could be simultaneously a *moisture source*, *an actor*, and a *building component* etc [29, 67]. This set of parameters, which describes the damage and its cause, was chosen based on the information available from the damage investigations.

The causes of damage should not be confused with the actual damage. Parameters and variables that describe technical aspects should not be confused with those that describe qualitative, structural, and human-related aspects, and vice versa [12]. In this paper, *inadequate maintenance* also includes poor, inaccurate, insufficient, and unsuitable maintenance. The variable *renovation* includes renovation, rebuilding, and restoration, as well as repairs of previously fixed or unfixed damage. Furthermore, the term *trustees* is used in this paper for those managing/upkeeping the buildings on-site. The variable *tenants* refer to the situation when it is not the property owner who occupies or lives in the building or apartment themselves. *Free water damage* is defined as damage caused by defects in pressurized or non-pressurized pipes and waterproof membranes [19, 49].

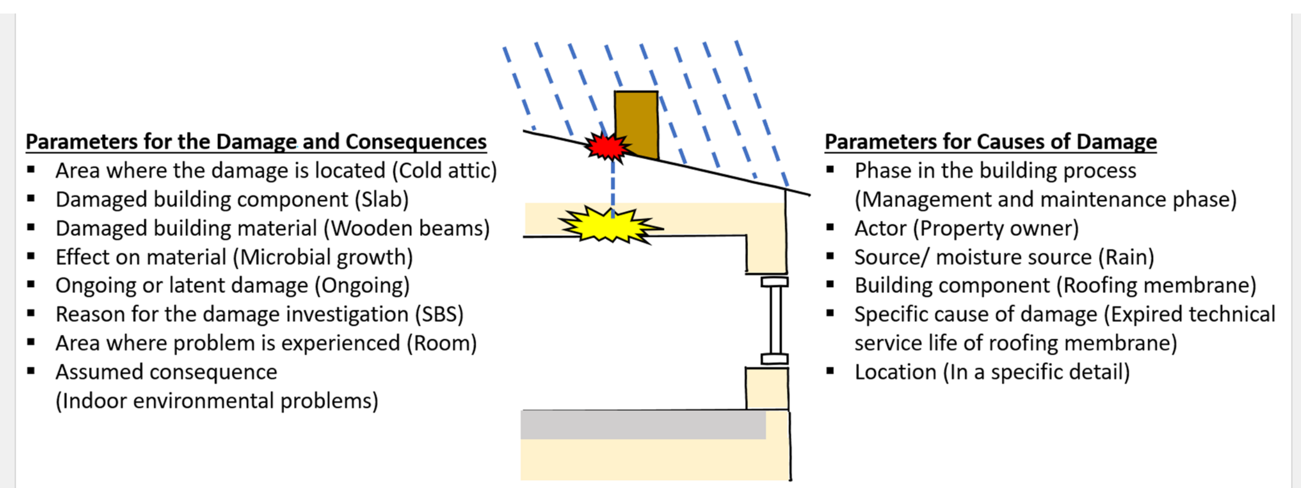

Fig. 1 Parameters in the sample/dataset. Parameters that describe the damage (yellow flash) are presented on the left, and parameters that define the causes of the damage (red flash) are shown on the right. Examples of variables for each parameter are given in parentheses after each parameter

3 Methods

The method consists of several different parts. Firstly, a dataset based on available information from real damage investigations was created. The dataset consists of 36 parameters, which mainly describe the buildings, the damage, and the cause of the damage using several different variables for each parameter. As a second step, the most interesting parameters concerning maintenance were analyzed and, where possible, cross-compared with one another. Based on the results, possible preventive actions were discussed.

3.1 Creation of the dataset

The dataset includes 2100 registered damage instances and causes of damage (CD) based on 428 real damage investigations. On average, each damage investigation includes 4.9 damage instances or causes of damage, which follows a similar trend found by Annila et al. [34, 35] who reported an average of 2.9 and 3.1 damage instances, respectively, for each reviewed investigation. Of the 428 damage investigations, 115 damage investigations had one damage and one cause of damage. However, one specific damage instance may also have two or more causes of damage, such as an uninsulated exterior basement wall with interior cracked plaster and paint caused by the absence of exterior insulation or deficient exterior drainage and vapor-tight interior paint. The dataset was initially presented by Mundt-Petersen et al. [29, 67] and Wallentén et al. [62], including 1105 CD. Subsequently, for this study, the dataset was expanded to a total of 2100 CD.

In total, 36 different parameters have been categorized in the dataset of 2100 CD regarding the damage instances, the cause of damage, and the buildings where the damage instances were found.

- 17 parameters concerning basic facts about the building, such as year built, use/purpose, ownership, geographic location, and the building design.
- 11 parameters presenting information about the damage, such as the reason for the damage investigation, what damage was noticed, the consequence of the damage, and the area where the damage was located.
- 8 parameters describing the cause of the damage, in which the five parameters; *phase in the building process*, *actor*, *source/ moisture source*, *building component* that caused the damage and the *specific cause of damage*, are analyzed in this study.

Each parameter includes several different descriptive variables. Possible uncertainties in quantifying the different types of damage were noticed in the dataset but were not analyzed in this study. To make the information from the damage investigations manageable, only the most significant variables were registered in the dataset. The parameters studied and their variables are further described in the results, as needed.

3.2 The sample of damage investigations from the dataset

The damage investigations cataloged in the dataset were primarily conducted between 2019 and 2021 (1998 CD). A few investigations spanned several years, which explains why a limited number of damage instances are listed between 2014 and 2018 (102 CD). Most damage investigations were conducted in 91 of Sweden’s 290 municipalities, mainly clustered in the densely populated regions of Skåne, Halland, Västra Götaland, Stockholm, Uppsala, Gävleborg, Dalarna, and Jämtland. A couple of the investigations were conducted in other parts of Sweden. The sample includes a wide span of different buildings including schools, single- and multi-family houses, pre-schools, offices, sports and swimming hall´s and hospitals and nursing homes. The majority of the buildings was constructed between 1960 and 2021. A more detailed description and distribution of the parameters in the dataset is given by Wallentén et al. [62]. The damage investigations were carried out by 15 accredited damage investigators [69], with different specialties and backgrounds, located in various parts of Sweden. The investigations were mainly initiated by scheduled moisture inventories, perceived SBS or BRI, visible free water, visible deformation, suspected odor or visible mold growth [67]. Based on the damage investigations the classifications and identifications of the damage and cause of the damage were conducted by the main author, which also is an accredited damage investigator and moisture safety expert. The damage investigations and the dataset are private (i.e. not public) and due to research ethical principles respecting the individual’s self-determination and integrity of inhabitants, property owners and damage investigators cannot be published. All investigated buildings and damage investigators are anonymized in the study.

The damage instances and causes of damage instances in the sample are complex and require the expertise of an accredited damage investigator. Less complicated damage instances associated with free water, such as leaks from pressurized pipes, wastewater pipes, wet room membranes, and floods from heavy rain, are often handled by moisture technicians and are readable in the Swedish Water Damage Center (SWDC) and the insurance companies’ statistics [19, 49], and therefore excluded in this study. Damage instances linked to radon are primarily excluded in the study, although complex instances of damage found during radon investigations have been included.

3.3 Analysis of the dataset

The analysis was conducted using sorted selections and pivot tables, which were cross-compared to identify correlations between different parameters and variables. The outcome from the selection and cross-comparison shows the frequency of different variables, for example, the frequency of damage caused by rainwater penetrating the roofing membrane due to inadequate maintenance. The cross-comparison could be executed in several steps for different parameters until the sample is too limited, similar to the multivariate analysis of damage among building types by Carretero-Ayuso et al. [44–46] and Wu et al. [70–72].

3.4 The choice of analyzed parameters

The study presents the frequency of different causes of damage that occurred in the maintenance phase. The dataset and its 36 parameters, along with numerous variables, can be cross-compared and further analyzed and evaluated in a multitude of different ways. To limit possible unnecessary and self-evident facts, this paper focuses on what is assumed to be the most valuable, required, and requested causes of damage assumed to be linked to maintenance, such as: *actors* caused damage, *phases* when damage occurs, *sources* caused damage, *building components* caused damage, and *specific* causes of damage.

The extensive material presents the main results mainly in charts, and further details in descriptive written text. If the sample becomes too limited, due to a lack of causes of damage, the study focuses on the critical and representative parts, and limited variables are not further investigated. The study develops results, presented by Mundt-Petersen et al. [29], where parameters deemed to be of interest are later analyzed and discussed in greater depth through cross-comparisons. The results were presented as percentages "%" and the number of causes of damage "CD". Percentages "%" were primarily used when comparing parameters to the entire sample (2100 CD) and when analyzing relative deviations and trends. The results for deeper analysis were mainly presented in the number of causes of damage, CD, to visualize the sample size, and avoid the possible confusion that "percentages of percentages" may cause.

3.5 Outlining preventive measures

The intention was to identify the primary causes of damage and discuss and propose preventive measures to minimize the amount of damage. Specific information and associated variables related to the chosen cause of damage in the dataset are presented along with the results and analysis in each subheading. Recommendations for preventing maintenance-related damage are presented in a separate section at the end of the paper.

4 Results and analysis

The results and the analysis are based on parameters for causes of damage identified in the right column in Fig. 1:

- *Phase in the building process*, when the cause of damage was deemed to occur.
- *Actor*, that was deemed to be responsible to cause the damage.
- *Source/ moisture source*, such as rain, tap water or dirt.
- *Building component*, which caused the damage.
- *Specific cause of damage*, including a more detailed description of the cause of the damage, such as defective assembly of roofing membrane, expired time of service life or inadequate cleaning.

This study focuses on the causes of damage that occur during the management and maintenance phase. For context, the causes of damage instances from the management and maintenance phase are presented together with the causes of damage instances from the other phases in Fig. 2. Although there might exist dependencies between the parameters, there is no obvious mutual order or strong causality. Further analysis of the parameter location of the cause of the damage, as shown in Fig. 1, was excluded since this is already studied in Mundt-Petersen et al. [29].

4.1 The correlation between actors and causes of damage in different phases

The basis of the study is derived from the distribution of damage by responsible actors across different phases for the entire dataset, as presented in Fig. 2. Around one-fourth (24%, 500 CD) of the damage instances were caused by *inadequate management and maintenance*, which was in good agreement with Sassu and De Falco [39] who showed that 32% (during the period 1990–1999) and 21% (between 2000 and 2011) of all damage were linked to lack of or failure in maintenance. However, the results are in contrast with those of Chong and Low [38], who found that only 4% of all damage is related to poor maintenance. Although 24% of all damage instances were caused by *inadequate management and maintenance*, which represents a significant proportion, it may be considered that the management phase is much longer compared to the design, construction, and renovation

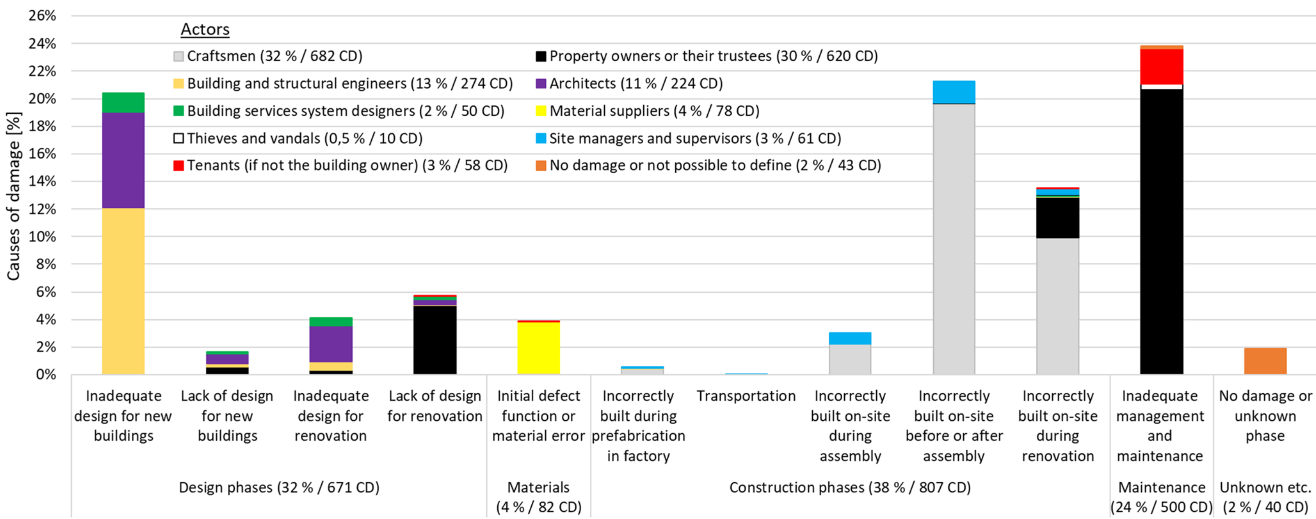

Fig. 2 Causes of damage addressed to *inadequate management and maintenance* in a context. The distribution of in which part of the building process the causes of damage instances occur cross-compared to the responsible actor causing the damage

phases, and a higher number of damage instances might be expected. On the other hand, if buildings are properly maintained, damage should be prevented. Given the high cost of damage, it is remarkable that there are such a limited number of relevant studies that consider damage caused during maintenance. A deeper investigation of this maintenance and management-related damage reveals the causes: *inadequate design for the renovation* (4%, 87 CD), *lack of design for renovation* (6%, 121 CD), and *incorrectly built on-site during renovation* (14%, 284 CD). Altogether, this distribution implied that 48% of all causes of damage occur in the *management and maintenance* phases, where half of it is linked to *inadequate management and maintenance* (24%) and the other half is associated with *renovation* (24%).

Almost all damage instances linked to *inadequate management and maintenance* were deemed to be caused either by *property owners or their trustees* (433 CD) or by *tenants* (54 CD). This is somewhat realistic, since the property owners are responsible for the maintenance of their own buildings. *Tenants* (54 CD) refers to the situation where the property owner and the *tenants* were two different actors. If the property owner lives in the house, which is common in *single-family houses*, the causes of damage are registered as the *property owner* and *their trustees* in the dataset. It was not possible to separate the *property owners* or *their trustees* (433 CD) into two distinct variables, as the damage investigations did not include this information. Although not analyzed in this study, it could be possible to separate other buildings from *single-family houses* and expect that the "*property owners"* live in their own houses. The limited number of damage instances caused by *thieves and vandals* (9 CD) was also included in management and maintenance. Those damage instances were mainly caused by *vandalism* (7 CD) and two other cases where the thieves stole installed water pipes filled with water to obtain the copper. The damage caused by *thieves and vandals* (1 CD) during the *renovation* was also linked to the theft of installed water pipes filled with water. Four damage (4 CD) were not possible to link to any specific actor.

4.2 Sources of damage during maintenance

By identifying sources and actors that commonly cause damage in the maintenance phase, as shown in Fig. 3, it is possible to determine which of them might be underestimated or frequently missed. Altogether, this helps to identify and emphasize preventive actions and control plans in the maintenance manuals and guidelines for buildings. The causes of damage, as shown in Fig. 3, correspond to each source, and the actors are described below.

4.2.1 Rain and snow

The results in Fig. 3 show that *rain and snow* (152 CD) were a significant moisture source, which caused damage due to *inadequate management and maintenance* by the *property owners or their trustees* (146 CD). Many of those damage instances were deemed to be caused by *wear and tear and inadequate maintenance* (117 CD), where the building components that caused the damage were not maintained or not replaced at the end of their technical service life. This is remarkable since those types of damage instances often are easy to discover and prevent, but are expensive to repair when the actual damage and its additional consequences occur. Five instances of damage were caused by *tenants* (5 CD) when free water occurred inside the building due to

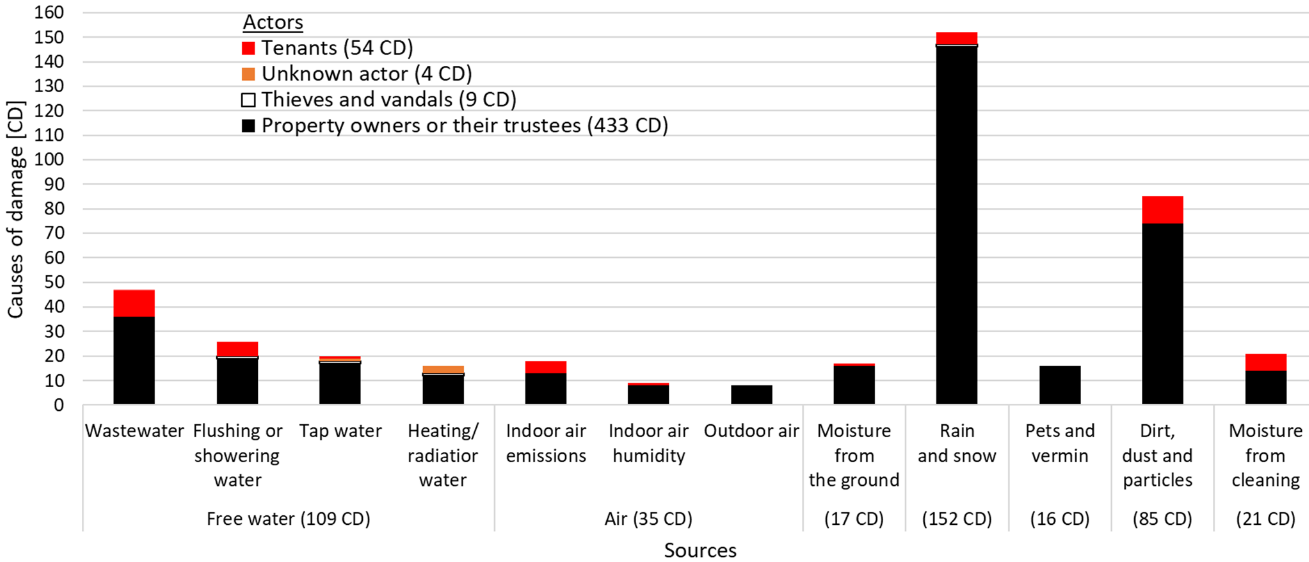

Fig. 3 The distribution of different sources causes damage by the actors during maintenance

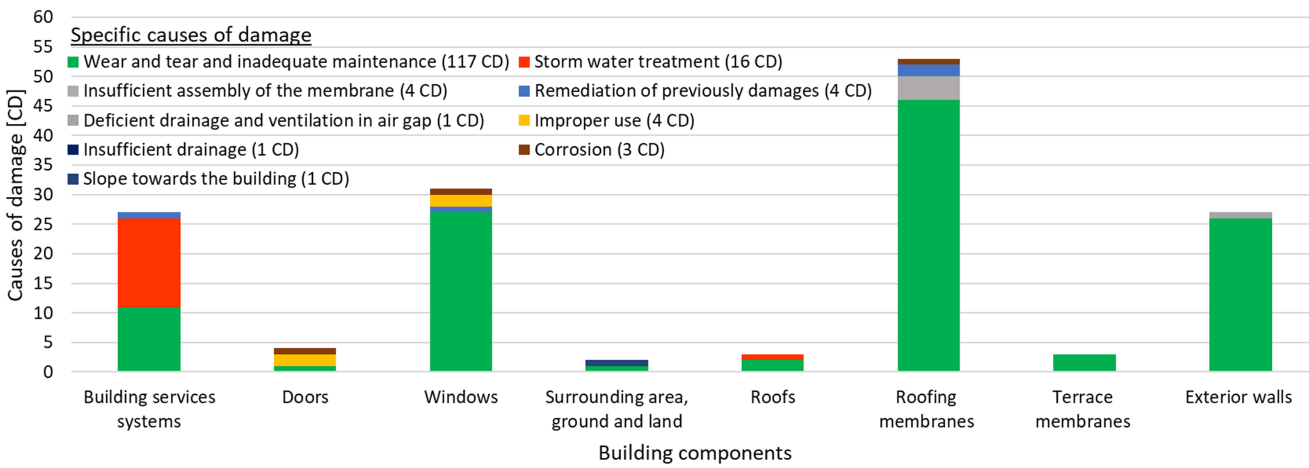

Fig. 4 A detailed analysis of the distribution of specific causes of damage linked to being caused by different building components due to rain and snow

open doors and windows, or wet materials being brought into the building. It is worth noting that the dataset shows a wide distribution in several parameters where instances of damage caused by *rain and snow* occur in several different parts of the parameters *rooms and locations* (14 variables), *building components* (14 variables), and *type of buildings* (15 variables).

Furthermore, Fig. 4 shows a more detailed analysis cross-comparing the parameters *building components* and *specific causes of damage* in the subset of *rain and snow* (152 CD).

Figure 4 shows that damage caused by *rain and snow* (152 CD) mainly consisted of *wear and tear and inadequate maintenance* (green/117 CD) and *stormwater treatment* (red/16 CD), predominantly located at *roofing membranes* (53 CD), *windows* (31 CD), *building services systems* (28 CD), and *exterior walls* (27 CD). Except for damage in *building services systems* (28 CD) that was heavily linked to *stormwater treatment* (red), the rest were caused by *wear and tear and inadequate maintenance* (green). This finding aligns with Sassu and De Falco [39], who also identified water penetration (48%) as a commonly reported defect.

4.2.2 Dirt, dust, and particles

Dirt, *dust*, *and particles* (85 CD) is the second leading source that caused damage due to *inadequate management and maintenance*. Damage caused by *property owners or their trustees* (74 CD) were identified as *inadequate cleaning* (54 CD) and *inadequate maintenance* (20 CD), while the rest of the damage instances were attributed to *tenants* (11 CD) mainly by *inadequate cleaning* (8 CD). The 85 CD linked to *dirt*, *dust*, *and particles* mainly consisted of *dirty* *ventilation pipes* (15 CD), *dirty ventilation filters* (11 CD), and *inadequate maintenance* of *stormwater treatment* (12 CD) due to leaves and other dirt in roofing drains, gutters, and downpipes.

4.2.3 Free water

The number of damage instances caused by free water may be underestimated, as these are primarily handled by moisture technicians and analyzed by the SWDC (1977–2022). However, a significant number of such damage instances were caused by *wastewater* (47 CD), *flushing or showering* (26 CD), *tap water* (18 CD), and *heating/radiator water* (16 CD). Damage instances from *wastewater* were mainly caused by different kinds of leakage from *wastewater pipes* (19 CD), *wastewater pipe blockages* (13 CD) mainly caused by *tenants* and *improper ventilation of wastewater pipes* (6 CD), and *wear and tear and inadequate maintenance* (6 CD) with an *exceeded technical service life*.

4.2.4 Air

Instances of damage caused by *indoor air humidity* (9 CD) and *outdoor air* (8 CD) refer to several reasons. Instances of damage caused by *indoor air emissions* (18 CD) were mainly due to *poor or total lack of ventilation*, where *tenants* (5 CD) often caused those damage instances by *blocking ventilation valves*.

4.2.5 Other observations of interest

Besides *blocking ventilation valves*, which caused increased *indoor air emissions* (5 CD), *tenants* (54 CD) mainly cause damage by *inadequate cleaning* (11 CD), *too much water when cleaning* (7 CD), and *wastewater pipes blockages* (9 CD). Damage caused by *pets and vermin* (16 CD), mainly due to mice, implies inadequate pest control by *property owners or their trustees*. Causes of damage when the *source was unknown* (7 CD) or no *relevant source was found* (53 CD), as well as the sources *solar radiation* (3 CD) and *settlements in the ground* (2 CD) with a limited number of causes of damage, were excluded from the chart in Fig. 3.

4.3 Building components cause damage during maintenance

Figure 5 shows the distribution of the most common building components that caused damage and therefore need more attention during maintenance. Building components with less than five causes of damage (in total 27 CD) and causes of damage without connection to a building component (in total 59 CD), such as *inadequate cleaning*, were excluded from Fig. 5. Variables with a limited number of causes of damage during maintenance, which were excluded from Fig. 5, give information about building components that, in general, do not give rise to problems. Examples of those are *indoor walls* (3 CD), *indoor roofs* (2 CD), *indoor stairs* (1 CD), *interior shafts* (1 CD), *slabs* (2 CD), *slabs-on-ground* (4 CD), *basement walls* (4 CD), *plaster or concrete plinth* (4 CD), *surrounding area*, *ground*, *and land* (2 CD)

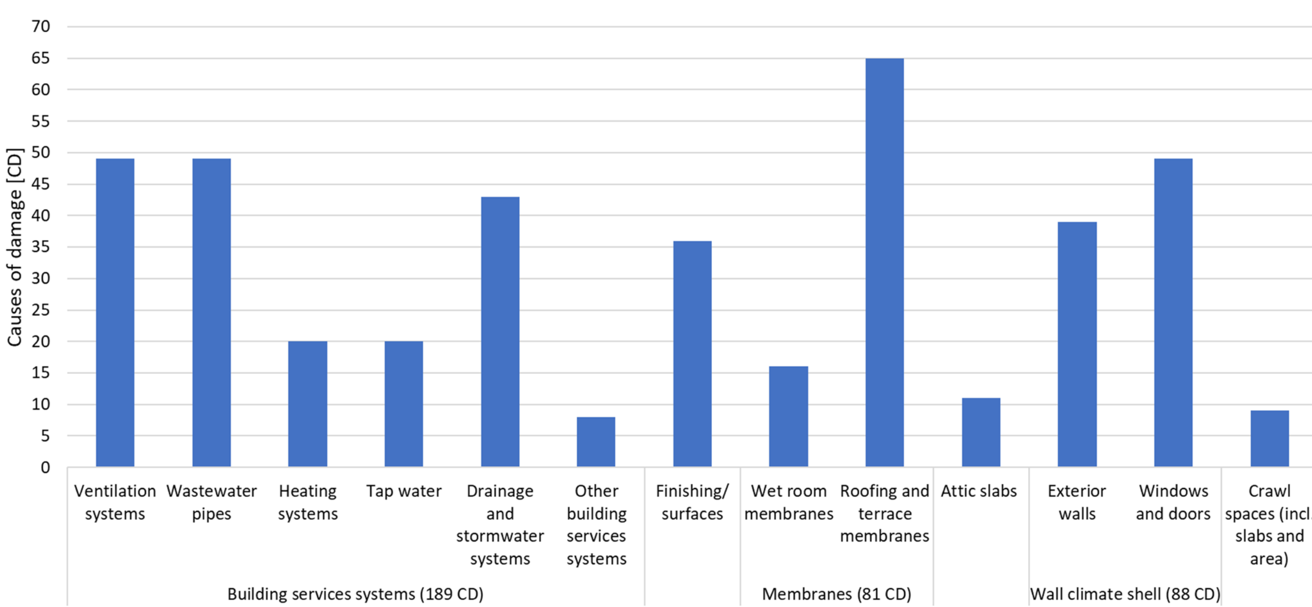

Fig. 5 The distribution of defective building components that cause damage

and *tongue and groove panels/roof decking* (1 CD) under the roofing membrane.

4.3.1 Building services systems

According to Fig. 5, *building services systems* (189 CD) of *ventilation systems*, *wastewater pipes*, *heating systems*, *tap water*, *drainage and stormwater systems*, and *others´ building services systems* were the primary defective building components. Damage caused by *ventilation systems* (49 CD) was mainly caused by *inadequate ventilation flow* (18 CD), *inadequately cleaned ventilation pipes* (15 CD), and *dirty ventilation air filters* (11 CD). More specifically, the fundamental causes of inadequate ventilation flow were due to *incorrectly adjusted ventilation flow* (8 CD), *blocked ventilation pipes* (6 CD), or *ventilation turned off* (4 CD). Damage caused by *wastewater pipes* (49 CD) mainly depended on *leakages from wastewater pipes* (19 CD), *wastewater pipes blockages* (13 CD), *defective pressure reducer of wastewater pipes* (6 CD), and *wear and tear and inadequate maintenance* (6 CD), where the technical service life has been exceeded. Damage caused by *heating systems* (20 CD) and *tap water* (20 CD) mainly refers to *leakage from pipes* (14 CD and 15 CD). Damage linked to free water is likely greatly underestimated in the dataset compared to real situations since those are generally handled immediately by moisture technicians and reported to and further analyzed by the SWDC [49]. However, since those causes of damage are found in the dataset, the results show that free water damage caused by, for example, *leakages from wastewater pipes* and *pressured pipes* of *tap water* also caused more complicated damage as investigated in this study. Lastly, damage caused by *drainage and stormwater systems* (43 CD) was mainly associated with *inadequate stormwater treatment* (20 CD), *damaged or defect gutters and downpipes* (17 CD), and *wear and tear and inadequate maintenance* (24 CD) including damage caused by *leaves and dirt in the gutters* (14 CD of 24 CD). In total 8 CD (19%) of the damage caused by *drainage and stormwater systems* (43 CD) were deemed to be related to an *exceeded technical service life*.

4.3.2 Wall climate shell

Almost all damage instances caused by *exterior walls* (39 CD) were linked to *wear and tear and inadequate maintenance* (35 CD), mainly associated with *expired technical service life* of the cladding (12 CD) and *inadequate maintenance façade* (10 CD). A similar situation was noticed for *windows and doors* (49 CD), where *wear and tear and inadequate maintenance* (40 CD) are also the dominating attributes.

4.3.3 Membranes

A significant number of damage instances were caused by *roofing and terrace membranes* (65 CD) due to *wear and tear and inadequate maintenance* (57 CD), of which more than half were associated with *expired technical service life* (29 CD). All instances of damage caused by *wet room membranes* (16 CD) were linked to *wear and tear and inadequate maintenance*. Although there is a high number of causes of damage due to membranes in different parts of the buildings, no damage was found to be caused by *inadequate membranes in the kitchen*. This is contrary to the SWDC [49], which found a high amount of damage in kitchens linked to *inadequate membranes*. Damage caused by *attic slabs* (11 CD) and *crawl spaces* (9 CD) were not deemed to be possible to analyze due to limitations in the sample.

4.3.4 Finishing/Surfaces

Most of the damage caused by *finishing/surfaces* (36 CD) during the maintenance refers to *wear and tear and inadequate maintenance* (32 CD). Further analysis shows that they were mostly due to *heavy wear and tear* (12 CD), *delayed lustering of linoleum flooring* (9 CD), and *expired technical service life* (5 CD). Analyzing the distribution of materials that became damaged shows that 32 CD consisted of damaged flooring, where 16 CD occurred in *linoleum flooring* and 11 CD in *PVC flooring*.

4.4 Specific causes of damage occurring during maintenance

The specific causes of damage include a detailed description of technical aspects such as *stormwater treatment* and *worn-out or damaged roofing membranes*. The differences between the parameters studied was illustrated in Fig. 1, where the *specific causes of damage* are not to be confused with previously presented main parameters or the actual damage. The 22 most common specific causes of damage due to *inadequate management and maintenance* were identified, of which technical causes of damage, such as *corrosion* and *inadequate ventilation flows*, are illustrated in Fig. 6, and actions or lack of actions, such as *inadequate cleaning* and *improper use*, are quantified in Fig. 7. The high level of detail emphasizes what needs to be improved to avoid problems during the management phase. The dataset includes a diverse set of specific causes of damage with less than four causes of damage (123 CD), such as *emissions from smoking neighbors*, *slope on the ground towards the building*, and *attic hatch not possible to close* which was excluded from further analysis.

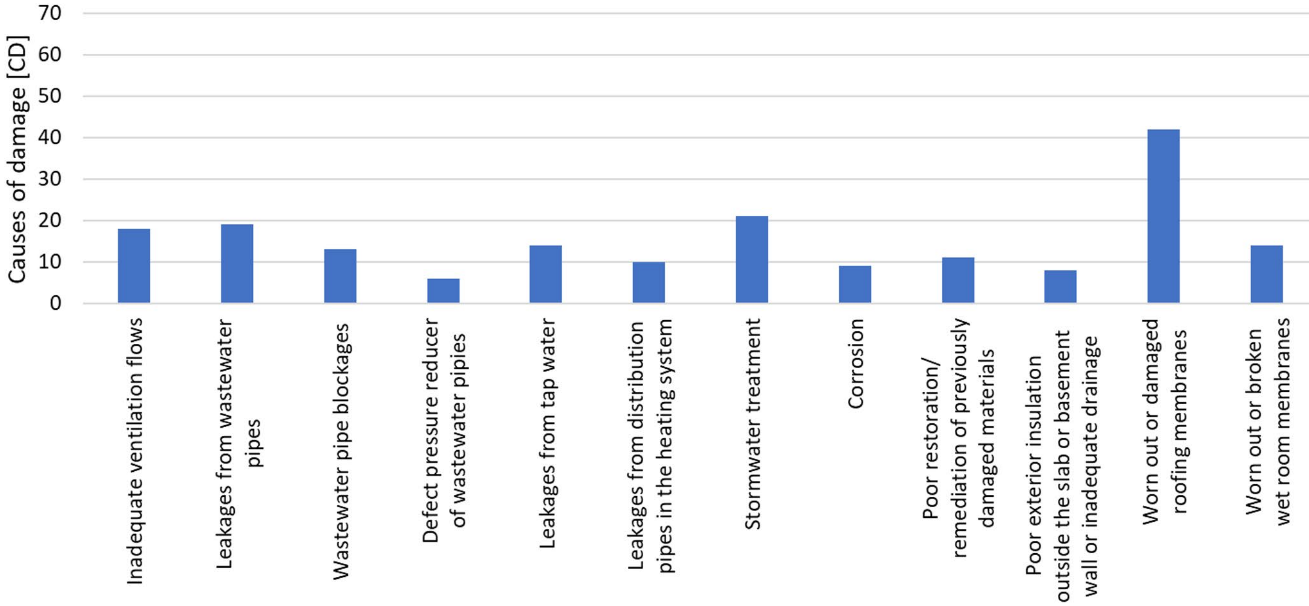

Fig. 6 The distribution of the most common specific "technical" causes of damage due to inadequate management and maintenance

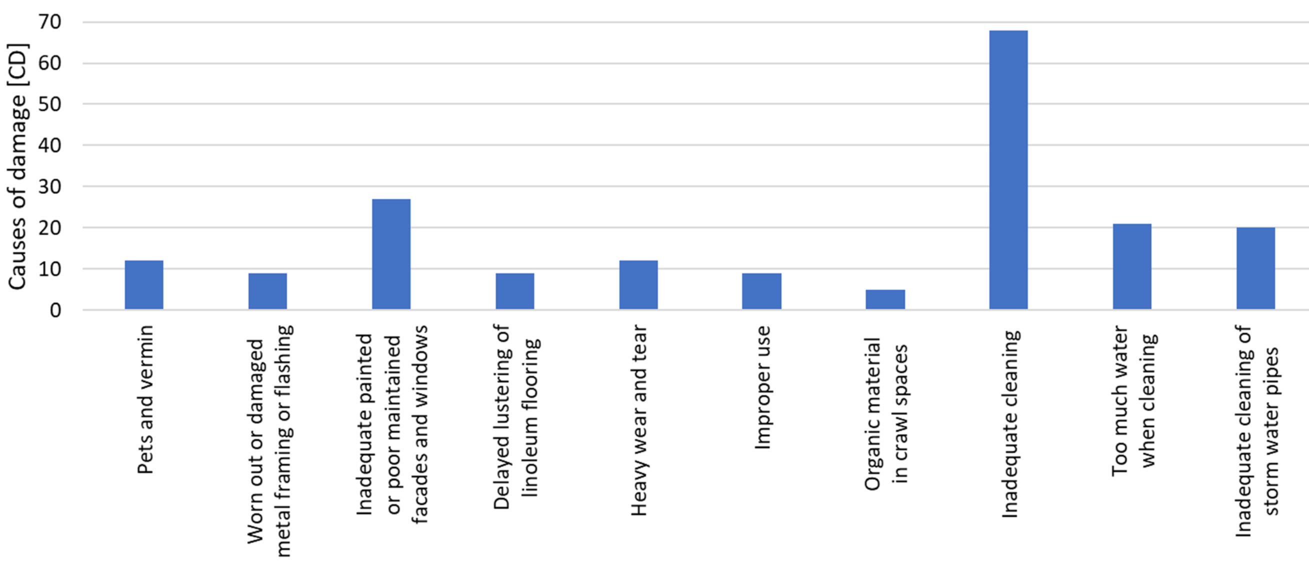

Fig. 7 The distribution of the most common specific causes of damage due to "lack of actual actions" during maintenance

Figure 6 shows that the highest number of damage instances was caused by *worn-out or damaged roofing membranes* (42 CD), in which most of these fell into the category *exceeding their technical service life* (29 CD). Damage caused by improperly maintained *stormwater treatment* (21 CD) refers to *damaged or defective roofing drains*, *gutters*, *and downpipes*, excluding leaves and dirt as presented above. The high amount of damage linked to precipitation is to be expected, as this represents a significant moisture load to which the building is exposed. *Inadequate ventilation flows* (18 CD) mainly occurred because the *ventilation was turned off* (4 CD), the *ventilation flow was incorrectly adjusted* (8 CD), or the *ventilation valves were blocked* (6 CD). The damage linked to *inadequate ventilation flows* (18 CD) is remarkable since the regulations demand regular controls of ventilation flows, and the results indicate that the law is neglected on this issue. *Leakages from wastewater pipes* (19 CD) were only described in detail for 2 CD, where the joint/connections between two pipes had separated, and another 2 CD where the technical service life was exceeded. *Wastewater pipe blockages* (13 CD) were found to be more commonly caused by *tenants* (9 CD of 13 CD) compared to the *property owners or their trustees* (4 CD of 13 CD). Three of the *defective pressure reducers of wastewater pipes* (6 CD) were due to damage located on the roof. *Leakages from tap water pipes* (14 CD) caused significant damage in one case, where the copper pipes were cut and stolen by *thieves and vandals* during the night and water flushed for several hours. The *leakages from distribution pipes in the heating system* (10 CD) excluded hot water tanks and district heating systems. Three of those causes of damage were linked to valves. Damage instances caused by *corrosion* (9 CD) were mainly linked to buildings services systems and doors and windows. Damage caused by *poor restoration/remediation of previous damage* (11 CD) refers to elementary actions such as removal and disposal of damaged materials and switched-off drying equipment. Damage caused by *thin exterior insulation outside the slab or basement wall or insufficient drainage* (11 CD) in the maintenance phase mainly refers to *organic materials that were placed on wetted slabs-on-ground* (3 CD). In four cases, those slabs and basement walls were deemed to have an exceeded technical service life. Different kinds of *worn-out or damaged wet room membranes* (14 CD) mainly refer to an *exceeded technical service life* (7 CD). In summary, most of the specific causes of damage were linked to the roof, membranes, or different building services systems.

Figure 7 shows that a significant number of damage instances were linked to *inadequate cleaning* (68 CD), such as *dirty ventilation pipes* (15 CD) and *dirty ventilation filters* (11 CD). Several instances of damage were caused by *too much water when cleaning* (21 CD), which damaged different building materials and furnishings. The issue of *too much water when cleaning* occurred in public buildings such as *schools* (12 CD), *preschools* (3 CD), and *care and nursing homes* (4 CD). All of these should have professional cleaning, and a sufficient quality of work might be expected. On the other hand, the cleaners might feel a lower sense of responsibility for the specific building thus lowering the quality of the cleaning. *Inadequate maintenance of façade and windows* (27 CD) mainly refers to infrequent painting and not replacing damaged panel boards. Several of those were also linked to an exceeded technical service life (11 CD). *Worn-out or damaged metal framing or flashing* (9 CD) was mainly caused by vandalism. *Improper use* (9 CD) includes windows and doors that were left open when it rained (4 CD). *Inadequate cleaning of stormwater pipes* (20 CD) mainly consisted of *moss growing on roofs* (6 CD) and *leaves and other dirt in roofing drains*, *gutters*, *and downpipes* (14 CD). *Pets and vermin* (12 CD) mainly consist of mice and insects. In summary, most of the causes of damage were linked to different kinds of inadequate cleaning, which should be easily addressed. Regarding technical service life, it was found that almost 20% (97 CD) of the entire sample of *inadequate management and maintenance* (500 CD) had causes of damage linked to *exceeded technical service life.* The high amount of elementary causes of damage makes it, in a broad context, questioned what competence some property owners have and what is included in the contract when hiring trustees.

5 Discussion

5.1 Definitions and parameters studied

Although the standard ISO 22185-1, Diagnosing moisture damage in buildings and implementing countermeasures, exists since 2021 [68], the definitions of damage and the nomenclature to describe it are not self-evident and vary across different studies. The variation may depend on factors such as the aim of the study, available data in the sample, and national rules and regulations [12]. The accredited damage investigators, who carried out the investigations collected in the dataset, have an equal understanding of the definition based on workshops in 2017 [69], which also corresponds to the ISO 22185-1:2021 standard [68]. In this study, the labels *failure* and *functional defects* were introduced due to the information in the damage investigations to create the dataset. *Failure* (8% of the entire sample of 2100 CD) was introduced as damage investigators, due to their code of conduct, are required to report obvious failures even though no damage has occurred. *Functional defects* (13% of the entire sample of 2100 CD) were established due to an insufficient indoor climate and odors resulting from factors such as a total lack of ventilation or inadequate ventilation, but without any damaged materials.

When determining the causes of damage, different aspects can be considered, such as technical or qualitative aspects. Mundt-Petersen et al. [12] observed that a high number of studies focus on human-related and qualitative aspects, such as poor motivation, stress, and inadequate systems or structures, and a limited number of studies with a technical focus are considered in this study. Andersson [43] and SWDC [49] stated that damage has decreased using reliable technical solutions and a quality control program based on technical information on the cause of the damage, such as Safe Water [73], BKR [74], and GVK [75]. The main purpose of this study is to identify technical aspects and specify key factors that cause damage due to inadequate maintenance. However, one reason for damage does not necessarily exclude the others, and regardless of the aspects studied, the high costs associated with damage confirm that all studies and reasons for the causes of damage are of interest. Therefore, there should be an acceptance of different aspects that provide reasons for what causes the damage.

5.2 Comparability between different studies

Different parameters and variables are generally chosen to describe the damage and the cause of the damage in different studies [12]. Although those might be named the same, they may have other contexts and definitions, such as if storm water treatment should be included in building services system or not. In our study, the categorization of storm water treatment influences the analysis when building services systems become affected by the moisture source rain and snow. Parameters for damage and causes of damage instances should in our view be separated. Similar approaches focus on causes of damage instances evaluated by cross-comparison and multivariable analysis were also carried out by Carretero-Ayuso et al. [44–46] and Wu et al. [70–72]. These analyses require a sufficiently large sample which needs a high level of detail to be useful. However, various climate, laws and regulations, and other conditions create situations where different parameters and variables should be studied. Parameters and variables may also vary depending on the information available in the sample, which is of interest when discussing the influence of the randomization of the sample. Consequently, studies with a sufficient sample and an adequate level of details [25, 33–42, 44–48, 64] but from different countries and with different parameters and variables difficult to compare to each other as well as this study. The fact that one specific damage instance may depend on different causes of damage makes the situation even more complicated. This could be of specific interest in cases handled in court, as described in studies such as Sassu and De Falco [39], Van Den Bossche et al. [40], De Vos et al. [41], and Carretero-Ayuso et al. [45]– [46] and when different actors blame each other for having caused the damage, as noticed by Love and Josephson [14]. Studies limited to free water damage are usually based on reports to insurance companies, which include an assumption of the damaged area and costs to repair [12, 36, 37, 43, 49]. The lack of information on the cost to repair in the damage investigations, which constitutes the sample in this study, made it difficult to compare the studies' focus on costs and with a lower level of detail, as seen in Boverket [1], Josephson and Hammarlund [15], and Hwang et al. [20]. The level of what is assumed to be a damage varies between different countries and Sweden has a tough definition of what should be assessed as damage. Due to Swedish laws and regulations, as well as information in the damage investigations, the dataset introduced *failure* and *functional defects*. The parameter *failure* exists in some other international studies, but has a different meaning compared to the Swedish definition [1, 12, 29, 62, 67]. *Functional defects* were not found in other studies using other datasets. Consequently, it may be questioned in what manner a poor indoor environment due to a lack of ventilation is defined in other studies, if considered at all. In summary, factors such as different definitions, parameters studied, laws and regulations, and potential limitations in the samples create a situation where it is difficult to make reliable comparisons between different studies. If comparisons are possible, they must be cautiously done [12].

5.3 The creation of the dataset

The selected parameters and variables in the dataset are chosen based on the available information in the damage investigations. Creating the dataset proved challenging, as it was difficult to define the parameters and variables to be included. Once the parameters and variables were chosen, it was easy to sort the damage based on the information from the damage investigations. The part of the study which considers what actor performed the actual action that caused the damage neglects whether the actor was instructed to act in a particular way by a supervisor or if other human-related and qualitative aspects were present, since it was not possible to determine in the damage investigations. Possible uncertainties could be identified in the dataset but were not evaluated further since the size of the sample suggested that these uncertainties would likely even out. While analyzing the dataset and reviewing all causes of damage, the overall reflection is that there is a high amount of damage that is at an elementary level and could easily be avoided. A parameter assessing the level of "elementary" for each cause of damage should have been included in the dataset. The high amount of damage linked to *building service systems* indicates that more data providing information about which systems for heating, ventilation, and so on are installed in the building should have been included. There should also have been a separate parameter considering the technical service life in the dataset.

5.4 The reliability of the dataset

Building research is often conducted through case studies or laboratory tests, although some similar studies with more extensive data from real-world cases are also available. The problem is having enough data to predict preventive actions that limit damage. The sample size of 2100 cases of damage is deemed to be sufficiently large so that possible uncertainties should be even out. To visualize the size of each part of the sample in the analysis, the number of damage instances is presented. A strictly limited number of damage instances also indicates parameters that might be of less importance.

As discussed in other studies [29, 62, 67, 70], the representativeness of the data must be considered, since in practice this type of data cannot be completely constructed from random samples. In this sample, the commissioner of the damage investigations mainly covers private individuals, authorities, insurance companies, and property owners. The distribution of those commissioners is due to the customer base of the damage investigation company. The commissioner's ability to order a damage investigation may also depend on several factors such as the complexity of the damage, the commissioner's capacity to repair and rectify the cause of the damage by themselves, the priority of the customer from the company carrying out the investigation, and the commissioner's ability to pay. Consequently, damage in single-family houses, simple damage, and damage with a low repair cost are expected to be underestimated in the database. Depending on what parameters are investigated, the reliability of the randomization may vary. In this sample, the local authority is an overrepresented customer, and the amount of damage in school buildings, which is deemed to be exposed to harder wear and tear compared to other buildings, may be relatively high in the sample. However, the building geometry and design of walls, slabs, roofs, and other elements in schools are somewhat similar to those in other buildings in Sweden. Therefore, depending on which parameters are investigated, the conclusions from the cross-comparison may need to be used cautiously. Since contractors and builders do not share their data on damage, probably due to the risk of negative publicity and lost capital of trust [1, 8], it is likely difficult to find a better sample or a sample with a higher level of detail than the one in this study. Studies based on real data are generally more reliable than those carried out using limited case studies or interviews and questionnaires, which have been shown to have possible inaccuracies and limitations.

6 Conclusions

In general, it was found that damage derived from maintenance can be attributed to numerous reasons and different causes of damage. A high amount of the studied causes of damage, although the specific number is not studied, were noticed to be on an elementary level and should be easy to avoid, such as *too much water when cleaning* and mainly all damage caused by an *exceeded technical service life*. Almost one-fourth of damage instances were related to *inadequate management and maintenance*, of which nearly all were the responsibility of the *property owners or their trustees*. Despite the amount of damage and possible costs of repairs, the field of *inadequate management and maintenance* is an unexplored area of research.

In total, 38% of management and maintenance-related damage found was associated with *building service systems*, making it a leading building component causing damage. For instance, *inadequate ventilation flows* due to *incorrectly adjusted ventilation flows*, and *turned-off ventilation*, or *blocked ventilation valves* result in a poor indoor environment. Apart from that, a high number of damage instances were linked to *stormwater treatment* and caused by *damaged or defective gutters and downpipes* or excessive *leaves and dirt in the gutters*. Damage was linked to *leakage in wastewater pipes*, *defective pressure reducers in wastewater pipes*, and *wastewater pipe blockages*, which account for 8% of all causes of damage. Moreover, almost 20% of all causes of damage were linked to an *exceeded technical service life*, mainly linked to *roofing and terrace membranes* and the *wall climate shell* due to *wear and tear and inadequate maintenance*. This indicates that *property owners or their trustees* should implement more effective preventive measures and regularly inspect, repair, or replace these exterior building components. Lastly, damage linked to *finishing/surfaces* mainly consists of damaged *PVC flooring* and *delayed lustering of linoleum flooring*.

Regarding the sources of damage, *rain and snow* were the most common sources that cause damage during the management phase. Most of those were linked to the building components *roofing membranes*, *windows*, and *exterior walls* and occurred due to *wear and tear and inadequate maintenance.* A high number of damage instances caused by *rain and snow* were also linked to poor *stormwater treatment*. Furthermore, *rain and snow* also cause a high number of damage instances linked to inadequate maintenance of *external walls* and *windows*. The results confirm that *rain and snow* are important sources that need to be considered during maintenance. A high number of damage instances were also caused by *inadequate or incorrect cleaning*. *Improperly cleaned surfaces* were found in several different locations inside the buildings, such as *leaves and dirt in the gutters*, *dirty ventilation pipes*, and *dirty ventilation filters*. Several instances of damage in different public buildings were also caused by *too much water when cleaning*.

Applying cross-comparison analysis to the dataset enables the investigation of correlations between different parameters and the identification of synergies between various inquiries to strengthen the findings. The size of the dataset is important, but it was enough to provide reliable results, even though there were some cases with a limited number of causes of damage where no strong conclusions could be reached. However, a limited number of causes for specific damage may indicate that the specific variables may be of less importance in causing damage.

7 Recommendations for preventive measures

Relevant recommendations and actions on how to prevent damage were provided to encourage the improvement of moisture safety practices to societal and industrial interests. These recommendations are based on the extensive results and detailed conclusions of the study. However, it may be challenging to determine which actions are most appropriate in every situation.

The high number of elementary causes of damage indicates that instructions for regular inspections and technical guidelines for maintenance need to be ensured. The guidelines need to include basic actions, such as cleaning and snow shoveling instructions, and be easy to understand. The high number of elementary causes of damage indicates that there is a lack of knowledge in the area, as well as a possible limited understanding of the importance of proper maintenance. This emphasizes the need for educational actions for both private and professional property owners, as well as administrative officers and trustees on-site. Most of the causes of damage were of such nature that they ought to have been possible to detect and thus prevented. This indicates that better regular inspections are required. One action in the inspections could be to estimate the remaining technical service life of inspected building components. Professional property owners may consider whether specific inventories should be carried out by external professional damage investigators every 5–10 years to ensure the quality of the building. However, besides some limited control of ventilation in buildings there are no such mandatory requirements of control or inventories in Sweden. Tenants may also need to be encouraged to report possible errors, which should be handled properly and professionally.

An extensive number of detailed recommendations for maintenance guidelines are presented below that have been determined from analyzing the dataset. Some of the recommendations refer to findings in the dataset that were too specific to be presented in the results:

- Regular camera inspections of ventilation pipes, including cleaning if dirty, should be carried out each year, as well as yearly replacement of ventilation filters.
- Regular inspections of ventilation flows, including measuring the real air flow through ventilation diffusers, should be carried out each year to ensure sufficient air quality.
- The humidity and indoor climate conditions in commercial kitchens might be better if the ventilation is increased some hours after the kitchen is closed and cleaning is finished, since a high amount of water may be used during cleaning.
- Pressurized pipes for tap water and heating should be visually inspected once a year.
- Water fault circuit breakers, which due to pressure or unrealistic water flows can detect a leakage, could be installed to limit the risk of free water damage from pressurized pipes by automatically shutting off the water supply in the building. Similar systems that send an alarm in case of pressure drops may also be installed on heating systems.
- External measurements and control of tap water flow and pressure drops, including detection and alarms when unrealistic water flows occur, could also be used by the local district water distribution companies. Similar systems could also be used by district heating companies.
- The status of wastewater pipes should be inspected regularly using a hose or sewer camera every 10 years. Older buildings with old wastewater systems may need to be inspected more frequently.
- The function of drainage of water into floor drains or directly to wastewater pipes from different machines, such as condensation water from cooling machines, should be controlled at least once a month.
- Cleaning *roofing drains*, *gutters*, *and downpipes* should be carried out at least twice a year. In the spring, during the snowmelt, ensure that there are no possible ice or snow barriers that block the water flow, and in the autumn after the leaves have fallen off the trees, remove possible leaves, dirt, and dust that may block *roofing drains*, *gutters*, *and downpipes.* If the building is located near a large number of trees, inspections should be carried out more frequently. It is also important to inspect the connections between downpipes and observe the flow of drained rainwater during heavy rain. These inspections should also include an inventory of the condition of *roofing drains*, *gutters*, *and downpipes.*
- Regular ocular inspections of *roofs* and *roofing membranes* should be performed at least once a year. If the roof is old, has solar panels, or has complex roof geometry, regular ocular inspections may be carried out every third to sixth month. Roofs with different ballasted solar panel systems on top of roofing membranes may be inspected after each storm to ensure that no movement of solar collectors has occurred and that parts of the solar cell installation are not abrading roofing membranes due to possible movement. At least some inspections of roofs should be carried out during heavy rain to evaluate how the rainwater flows and detect possible leakages. Old roofing membranes or roofs with solar panels mounted on top of roofing membranes on compact roofs can be inspected using air pressurization and smoke machines to detect possible suspected leaks. During days with temporary rain and large temperature differences,

conditions exist to successfully use thermography as a tool to find leaks.

- The climate shell (exterior walls, roofs, plinth, windows, doors, etc.), should be inspected each year with a focus on details, connections, and joints such as metal flashings, eaves, and roofing ridges to ensure that any defective parts do not cause incorrect water flows into or towards the façade or building. Particular attention should be given to the quality of expansion joints and other façade joints between concrete blocks, as leakage through these could cause damage that is difficult to detect.
- During the summer period, it should be ensured that there is a slope directed away from the building pitches and that vegetation, such as bushes and trees, are far enough away from the façade and roof.
- The status of bathrooms and other wet rooms should be inspected for cracks and settling yearly. This inspection should include the function of floor drains and shower channels, including the clamping ring, which creates a watertight connection with the waterproofing membrane.
- Regular cleaning should be carried out daily in schools and other public buildings and at least once a week in multifamily houses and single-family houses. The frequency of cleaning may vary depending on the activities or the building's purpose. The frequency of cleaning and specific cleaning actions may also vary depending on the season and daily weather. The technical guidelines should include instructions on how to treat and clean different materials and machines regularly. Floor drains and shower channels should be cleaned of dirt, hair, and so on. Possible leakage indicators in shafts and manifold cabinets should be inspected during cleaning and immediately reported to the trustees in charge if a leakage is noticed. Lint filters and other filters in the kitchen and washing machines should be checked, replaced, and cleaned weekly, as needed. Cleaning also includes things other than the cleaners, such as trustees who deal with ventilation pipes, ventilation filters, roofing drains, gutters, and downpipes, but also residents and kitchen staff who wipe the tables and do the dishes.
- Almost all buildings have different kinds of unavailable areas and places that need to be cleaned, such as cavities and on top of suspended ceilings or hanging lighting fixtures, where layers of dust may accumulate over time. Those unavailable areas and places should be listed in the cleaning instructions, and the person responsible for cleaning them should be identified.
- Exposed cavities in commercial kitchens are checked visually and cleaned at least once a year.
- Information about the frequency and method of lustering flooring should be made clear.
- Information about how often building components such as façades should be painted or joints replaced should be given, and instructions for how this maintenance should be carried out.
- Instructions for snow shoveling, including what tools to use, what area to shovel, and where to temporarily store shoveled snow, should be provided.
- Maintenance of guillotines dealing with *pets and vermin*, as well as treatment of the remaining corpses, should occur.
- Clear instructions should be provided on how to act and who to contact if damage and the causes of damage are noticed. This should include an emergency plan outlining what to do in the event of a free water leak or similar occurrence. In the event of an acute water leak, the water should be turned off immediately, and the trustees in charge and a professional moisture technician should be contacted. The faster professional help is contacted and the faster cleanup of free water and drying begins, the better the chances of limiting the consequences of the damage.

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Data availability The damage investigations that were collected in a dataset for the study were carried out by 15 accredited damage investigators with different specialties and backgrounds, located in various parts of Sweden. The dataset could be show if requested and all specific numbers presented in the study could be given and derived if requested. However, the damage investigations and the dataset are private (i.e. not public) and due to research ethical principles respecting the individual's self-determination and integrity of inhabitants, property owners and damage investigators cannot be published. All investigated buildings and damage investigators are anonymized in the study.

Declarations

Conflict of interest The authors declare no competing interests.

Ethical approval The study deals with buildings as the subject and does not consider humans or animals issues.

Consent to participate Not an issue.

Consent to publish Not an issue.

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