

Article

A Standardized Framework for Facade Pathology Assessment Based on Visual Inspection, Damage Classification and Cluster Analysis

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Abstract

Building facades are highly exposed envelope components whose degradation affects durability, habitability, urban image, and maintenance planning. Several studies address facade anomalies and service-life prediction. However, a need remains for integrated, reproducible procedures that combine visual inspection, taxonomic classification, and statistical analysis within a single framework. This research develops and validates a standardized methodology for the assessment of facade pathologies in urban buildings. The proposed framework is structured into sequential phases: documentary research, systematic visual inspection, photographic recording, damage classification, facade mapping, standardized inspection sheets, database generation, statistical analysis, and cluster-based interpretation of damage patterns. The methodology was validated through an urban case study in Valencia, Spain, where 168 building facades were inspected and 1600 damage were identified, classified, mapped, and digitized. The collected data were analysed according to building age, environmental exposure, and affected facade units. Soiling due to differential washing was the most frequent damage type, with 295 cases. Buildings constructed between 1930 and 1960 concentrated the highest number of recorded cases (639), while the wall area near ground level was the most affected facade unit (499 cases). K-means analysis retained a three-cluster solution, with a Silhouette Score of 0.65 and a BSS/TSS ratio of 86.13%. In addition, K-means cluster analysis was applied to classify damage types according to their frequency after Z-score standardization and validation through Silhouette Score and BSS/TSS metrics. The results demonstrate that the proposed framework enables homogeneous data collection, reproducible classification, and diagnostic interpretation of recurrent facade damage. Beyond the specific findings of the Valencia case study, the main contribution of this work is the development of a transferable assessment framework that can support preventive maintenance protocols, inspection planning, and evidence-based conservation strategies in other urban contexts.



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Keywords: facade pathology; building envelope; visual inspection; standardized inspection sheets; damage classification; damage mapping; urban buildings; cluster analysis; preventive maintenance; condition assessment

1. Introduction

Research Context

Building facades constitute one of the most exposed components of the building envelope and play a decisive role in durability, habitability, energy performance, urban image, and the long-term maintenance of the built environment. Continuous exposure to environmental agents, construction defects, and poor maintenance favors the development of pathological processes. These issues eventually compromise both the technical performance and visual quality of buildings [1,2].

The diagnosis of facade pathologies is therefore a key stage in preventive conservation and maintenance planning. Early identification of visible damage, its location, extent, recurrence, and possible relationship with environmental or constructive factors allows technicians to establish more informed intervention criteria and to prioritise repair actions. This is particularly relevant in urban building stocks affected by ageing processes, heterogeneous construction systems, and varying degrees of exposure to pollution, wind-driven rain, solar radiation, marine aerosols, and traffic-related deposits.

Several studies have addressed the degradation of building envelopes and have proposed different approaches for identifying damage [3], assessing service life, or modelling the influence of environmental agents on facade deterioration [2,4]. These contributions have provided a valuable basis for understanding pathological processes and for developing maintenance strategies [5]. However, the practical diagnosis of facade degradation in consolidated urban areas still requires procedures that are capable of integrating visual inspection, damage classification, graphic mapping, data codification, and statistical interpretation within a coherent and reproducible workflow [6].

In this context, visual inspection remains a technically viable and cost-effective method for large-scale preliminary assessment. Although non-destructive testing (NDT) techniques, such as infrared thermography, ground-penetrating radar, ultrasonic testing, or other instrumental methods, may provide higher diagnostic precision in specific cases [7,8], their systematic application to large urban samples entails significant economic, logistical, and operational constraints. Visual inspection, when supported by standardized criteria, photographic documentation, graphic mapping, and structured data sheets, can provide reliable information for detecting visible damage and for identifying patterns that may guide subsequent detailed analyses [9,10].

2. Related Work, Research Gap and Contribution

Previous research on facade degradation has followed different methodological approaches. Some studies have focused on specific finishing materials or cladding systems, such as cement-rendered facades, painted coatings, concrete facades, ceramic systems, or natural stone claddings [3,9,11–13]. These works have contributed to the definition of degradation indicators, service-life prediction models, risk maps, and maintenance strategies for particular constructive solutions. However, their applicability is often linked to specific materials, exposure conditions, or degradation mechanisms, which may limit their transferability to heterogeneous urban building stocks composed of different facade typologies, construction periods, and maintenance histories.

Other studies have proposed visual inspection systems based on qualitative and quantitative assessment scales, enabling the classification of anomalies and the evaluation of degradation levels in selected building envelope components [14,15]. Global inspection systems, defect atlases, and harmonised classification procedures have also been developed to improve the consistency of building pathology diagnosis and to connect defects, probable causes, diagnosis methods, and repair strategies. These approaches provide a valuable methodological basis. Nevertheless, they are generally oriented towards broad building

inspection systems or defect cataloguing, rather than towards the spatial codification, statistical treatment, and cluster-based interpretation of facade damage patterns within large urban street samples.

A further line of research has analysed facade pathologies through large datasets obtained from claims, complaints, insurance records, or legal proceedings [2]. These approaches are useful for identifying recurrent damage combinations and their possible original causes [16]. Nevertheless, they tend to be conditioned by the nature of the source data, as they usually include only damage reported by users or recognised through administrative, legal, or insurance procedures. Consequently, minor, early-stage, or non-reported defects may remain outside the analysis.

Defect mapping and risk mapping studies have contributed to identifying vulnerable facade areas and spatial concentrations of damage [3]. These methods are particularly useful for visualizing the distribution of anomalies and supporting maintenance decisions. However, in many cases, mapping is applied to specific materials, cladding systems, or case-study conditions. Moreover, mapping procedures are not always integrated with standardized inspection sheets, codified databases, statistical interpretation, and diagnostic prioritization within a single reproducible workflow.

Recent research has increasingly addressed the use of technology-assisted and automated approaches for facade inspection [16–18]. Other works have explored the use of UAV-based image acquisition, BIM environments, remote sensing, image-based mapping, and deep learning techniques to support damage documentation, automated detection, and conservation assessment [19–23].

More recent studies have further developed these approaches through drone-based image acquisition and deep learning [24], infrared thermography applied to high-rise building facades [25], YOLOv8-based detection and quantification of damage in historic brick walls [26], deep learning-based crack detection on cultural heritage surfaces [27], and UAV-acquired datasets developed for machine learning-based defect detection [28]. These methods can improve inspection efficiency, reduce access risks, and enhance the detection of certain damage types. However, they also present limitations related to acquisition conditions, image quality, training datasets, annotation requirements, model transferability, and the difficulty of detecting multiple defect types across heterogeneous facade materials and urban contexts. In particular, automated systems often require high-quality labelled datasets and may show reduced performance when applied to facade types, materials, or damage categories that differ from those used during training.

Therefore, despite these advances, a methodological gap remains. There is still a need for integrated and reproducible frameworks capable of combining direct visual inspection, taxonomic damage classification, facade mapping, standardized inspection sheets, database generation, statistical treatment, and cluster-based interpretation within a single diagnostic workflow [29]. The proposed framework addresses this gap by transforming expert visual inspection into structured and analysable data, while maintaining the capacity to interpret construction context, facade units, material discontinuities, exposure conditions, and singular interventions that may not be fully captured by automated detection systems.

Compared with existing global inspection systems, the proposed framework is specifically focused on facade pathology assessment at the urban sample scale. Compared with defect atlases, it not only catalogues damage types, but also records their location, affected construction unit, environmental exposure, and frequency. Compared with defect mapping approaches, it integrates graphic mapping with standardized data sheets and a structured database. Finally, compared with purely descriptive inspection methods, it incorporates statistical analysis and K-means clustering to classify damage types according to their recurrence and maintenance relevance. In this sense, the contribution of the study is not

limited to the Valencia case study, but lies in the development of a transferable diagnostic framework for evidence-based facade assessment and preventive maintenance planning.

Based on the research gap identified above, the aim of this study is to develop and validate a standardized methodology for the inspection, classification, codification, mapping, and statistical analysis of facade pathologies in urban buildings. Rather than focusing exclusively on the identification of the most frequent damage in a specific city, the research proposes a transferable diagnostic framework capable of supporting facade condition assessment in different urban contexts.

The proposed methodology is based on four main contributions. First, it establishes a taxonomic classification system for facade damage, structured according to the nature of the pathological process and codified to facilitate subsequent statistical analysis. Second, it develops a standardized inspection framework based on data sheets that ensure homogeneous recording of building characteristics, environmental exposure [30], damage type, affected construction unit, photographic documentation, and graphic mapping. Third, it converts the information collected during fieldwork into a structured database, allowing the correlation between damage types, building age, environmental exposure, and facade units. Fourth, it incorporates cluster analysis as a data-driven tool for classifying damage types according to their frequency and diagnostic relevance.

The methodology was validated through an urban case study in Valencia, Spain. The validation sample comprised 168 building facades located in selected urban areas and included 1600 identified damage cases. These cases were visually inspected, photographed, classified, mapped, codified, and incorporated into a database. The Valencia case study is therefore used as a validation environment for testing the applicability, robustness, and diagnostic potential of the proposed framework.

By combining systematic fieldwork with standardized data collection and statistical interpretation, this study provides a reproducible methodology for facade pathology assessment. The resulting framework can assist technicians, researchers, planners, and public administrations in identifying recurrent damage patterns, locating critical facade areas, prioritising maintenance actions, and improving preventive conservation strategies in urban building stocks.

3. Materials and Methods

3.1. General Structure of the Proposed Framework

This research proposes a standardized framework for the inspection, classification, codification, mapping, and statistical analysis of facade pathologies in urban buildings. The framework was designed to transform visual observations into homogeneous, quantifiable, and reproducible data, allowing damage patterns to be identified, compared, and interpreted across different buildings, facade units, and exposure conditions.

The methodology integrates several stages into a single diagnostic workflow. These include documentary research, visual inspection, damage classification, and statistical analysis. Therefore, the aim is not only to record the pathological condition of individual facades, but also to develop a transferable assessment procedure capable of supporting preventive maintenance protocols, inspection planning, intervention prioritization, and evidence-based conservation strategies.

The proposed framework was validated through an urban case study in Valencia, Spain. In this research, Valencia is used as a validation environment for testing the applicability and diagnostic capacity of the methodology. The case study included a heterogeneous urban building stock, different construction periods, and varied environmental exposure conditions. Within the selected urban areas, 238 buildings were initially identified, and 168 facades presenting visible pathological conditions were finally recorded and analysed.

Facades without visible pathological conditions were not included in the damage database because no damage case could be classified, mapped, or codified. Therefore, the dataset should be understood as a pathology-based analytical sample aimed at validating the proposed inspection and classification framework, rather than as an exhaustive prevalence survey of all buildings within the selected urban areas.

A total of 1600 damage cases were identified, classified, mapped, codified, and incorporated into the database. In this study, a damage case corresponds to the presence of a specific damage type in a defined facade construction unit of a particular building. Multiple manifestations of the same damage type within the same facade construction unit were counted only once, regardless of the number of separate areas in which they appeared. However, the same damage type was recorded as a separate case when it affected a different facade construction unit. Likewise, different damage types affecting the same facade construction unit were recorded separately. Percentages were calculated using different denominators according to the purpose of each analysis. Depending on the case, they refer to the total number of recorded damage cases ($n = 1600$), the total number of cases within a specific damage category, or the number of buildings within a given construction-period or exposure group. Since only the principal facade of each building was considered, the building and facade counts are equivalent in this study ($n = 168$). The corresponding denominator is specified in each case in the Results section.

The overall methodological workflow is summarized in Figure 1. This figure presents the complete diagnostic sequence, from input data and documentary research to visual inspection, damage classification, standardized data recording, statistical analysis, cluster analysis, and final diagnostic interpretation.

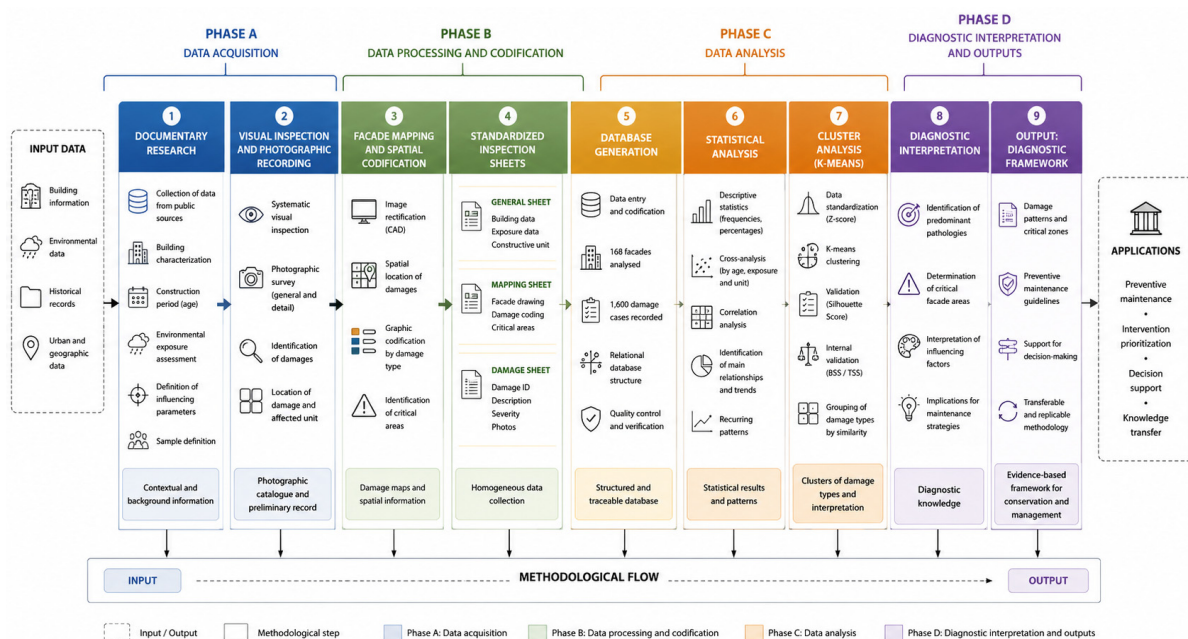


Figure 1. Standardized facade pathology assessment framework. The workflow shows the sequential process from input data and documentary research to visual inspection, photographic recording, damage classification, facade mapping, standardized inspection sheets, database generation, statistical analysis, cluster analysis, and final diagnostic interpretation.

3.2. Documentary Research, Visual Inspection and Facade Mapping Workflow

The data collection workflow was structured into three consecutive and interrelated stages: documentary research, visual inspection with photographic recording, and facade mapping. These stages were designed to progressively transform preliminary building

information and field observations into spatially codified data suitable for standardized recording and subsequent analysis.

The first phase consisted of documentary research aimed at characterizing the buildings and their urban environment before field inspection. Publicly available sources were consulted to obtain information on each property, including location, construction date, building height, urban context, and environmental exposure conditions. The main sources included cadastral information, municipal records, and digital databases provided by the local administration.

The sample was defined within urban areas corresponding to different stages of Valencia's urban development. Complete urban blocks and entire street sections were selected, and all buildings located within these areas were considered, regardless of whether they presented visible pathological conditions. The selection therefore included buildings with and without visible damage, as well as different construction periods, facade typologies, and finishing materials. This territorial selection criterion avoided the preselection of only deteriorated buildings and allowed the framework to be tested on a heterogeneous urban sample.

The documentary phase provided the contextual information required to complete the general inspection sheet and to establish the influencing parameters used in the subsequent analysis. These parameters were grouped into three main categories: building age, environmental exposure, and affected construction unit.

Once the documentary information had been compiled, the second phase consisted of systematic visual inspections of the selected facades. Visual inspection was adopted as the primary diagnostic method because it allows large urban samples to be assessed in a technically feasible, cost-effective, and reproducible manner. Although instrumental non-destructive testing techniques can provide greater diagnostic precision in specific cases, their systematic application to extensive urban samples is often limited by economic, logistical, and operational constraints. In this context, visual inspection provides an appropriate preliminary assessment method when it is supported by standardized criteria, photographic documentation, graphic mapping, and structured data recording.

For each building, a photographic catalogue was created, including both general views of the facade and detailed images of each identified damage case. The photographic record was used not only as visual evidence, but also as a support for the subsequent mapping and classification process. This procedure ensured that each observed pathology could be documented, located, checked, and incorporated into the database in a consistent manner.

The visual inspection protocol included the identification of the type of damage, its position on the facade, the affected construction unit, and its relationship with the building and environmental parameters previously recorded during the documentary phase.

The information obtained during the photographic survey was used as the basis for the graphic representation and spatial codification of the observed damage. The photographic rectification and facade mapping procedure was carried out in two stages. First, general facade photographs were rectified using Adobe Photoshop in order to correct perspective distortion and obtain a frontal image suitable for graphic analysis. The rectified images were then exported to a computer-aided design (CAD) program, where they were scaled using known real dimensions, such as facade width, openings, or other measurable architectural elements. This process allowed the facade to be drawn and analysed at real scale.

Damage areas were mapped directly over the rectified and scaled facade image, recording both their location and their visible extent. Each type of damage was represented using a specific graphic code, enabling the identification of recurrent pathological patterns and their concentration in specific facade areas. This step is particularly relevant for the

diagnostic value of the framework, since it links damage type with construction location and allows critical areas to be identified.

When occlusions were present, such as vegetation, urban furniture, parked vehicles, or projecting elements, the mapping was completed with the support of detailed photographs. The resulting damage maps were subsequently verified during a second on-site inspection, in which the preliminary drawings were checked in situ against the actual facade conditions. This verification step improved the reliability of the spatial location and visible extent of the mapped damage and reduced potential errors derived from photographic interpretation or graphic representation.

The relationship between documentary research, fieldwork, mapping, classification, and standardized inspection sheets is detailed in Figure 2. Unlike Figure 1, which presents the general diagnostic framework, Figure 2 focuses specifically on the operational data collection workflow and the way in which the information is progressively incorporated into the inspection sheets.

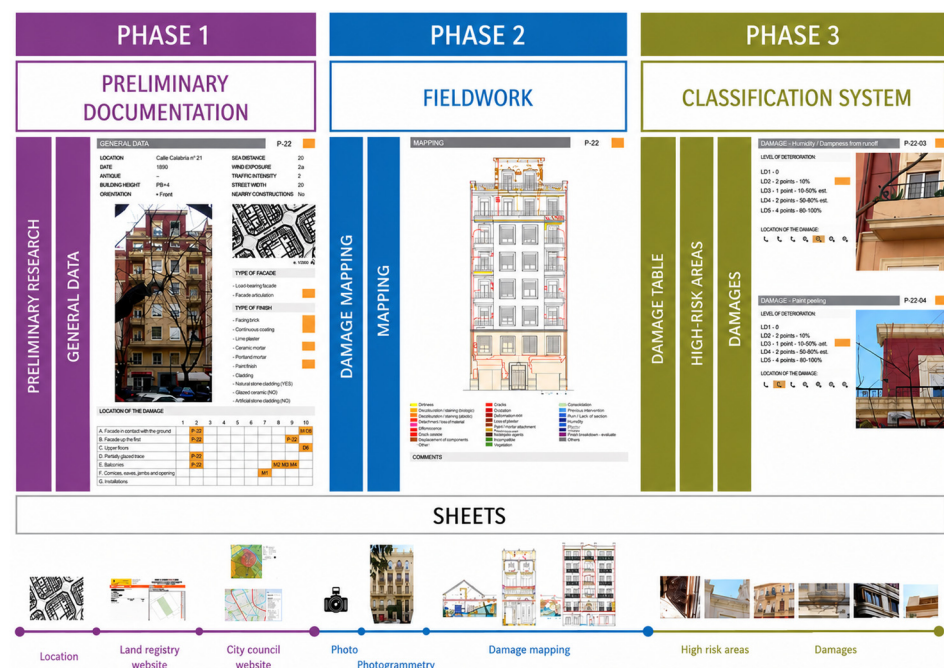


Figure 2. Standardized inspection sheets and data collection workflow. The figure shows the three main stages of the inspection and recording process: documentary research, visual inspection and fieldwork, and damage classification. The workflow integrates building and exposure data, facade damage mapping, identification of high-risk areas, and individual damage records into a standardized set of inspection sheets.

The visual inspection was coordinated by the same principal researcher throughout the study, with the support of other members of the research team during fieldwork and subsequent data verification. Before the inspection campaign, the damage taxonomy and the standardized data collection sheets were defined on the basis of the published scientific literature and the classification criteria presented in the following section. This prior definition of damage categories, facade units, and recording fields was intended to reduce the subjectivity of visual inspection and ensure homogeneous data collection. Each recorded damage case was documented using general facade photographs and detailed images. During the subsequent data processing stage, the records were reviewed against the photographic documentation and the facade maps. Ambiguous cases were reviewed by the principal researcher with the support of the research team before being incorporated

into the final database. This verification procedure was used as a quality-control step to improve consistency in damage classification, mapping, and codification.

3.3. Influencing Parameters and Damage Classification System

For the subsequent statistical and diagnostic analysis, the proposed framework combines two complementary coding levels. First, the parameters that may influence facade degradation were defined and codified. Second, a structured damage classification system was established in order to ensure homogeneous identification and recording of the pathological processes observed during fieldwork.

Three groups of influencing parameters were considered in the framework: building age, environmental exposure, and construction unit.

Building age was used to analyse the relationship between construction period and facade degradation. The buildings were grouped into four age categories: before 1930, 1930–1960, 1960–1990, and after 1990. This classification allowed the influence of construction period, material ageing, and maintenance history to be assessed.

Environmental exposure was considered through parameters related to the urban and climatic context of each facade. This included orientation, distance from the sea, wind exposure, and traffic intensity [13]. These variables were incorporated because they may influence moisture behavior, surface soiling, biological growth, corrosion, material erosion, and other degradation processes.

The construction unit refers to the specific facade area where damage occurs. Seven facade units were defined: wall near ground level, cornice or roof parapet, continuous wall, overhangs, balconies, corners, edges and openings, and installations. This classification enabled the analysis of the relationship between damage types and critical facade points [2,13].

The coding system used for the influencing parameters is presented in Table 1.

Table 1. Coding and description of the influencing parameters used in the research.

PARAMETER	CODE	CONCEPT
Parameter 1	Code	Description
	A.1	Before 1930
	A.2	1930–1960
	A.3	1960–1990
	A.4	After 1990
Parameter 2	Code	Description
Orientation	NE/E/SE	Northeast/East/Southeast
	N	North
	SW/W/NW	Southwest/West/Northwest
	S	South
Distance to sea	1P	less than 1 km
	2P	less than 5 km
	3P	more than 5 km
Wind exposure	1V	Attached buildings, street width < 20 m
	2V	Attached buildings, street width > 20 m
	3V	Corner/Attached buildings, street width < 50 m
	4V	Corner/Attached buildings, street width > 50 m
Traffic intensity	1	1–1500 vehicles/hour
	2	1501–3000 vehicles/hour
	3	3001–4500 vehicles/hour
	4	4501–6000 vehicles/hour

Table 1. *Cont.*

PARAMETER	CODE	CONCEPT
Parameter 3	Code	Description of the construction unit
Construction units	Z1	Wall near ground level. Bottom (floor level)
	Z2	Cornice or roof hangings. Top (parapets/eaves)
	Z3	Continuous wall
	D1	Hangings
	D2	Balconies
	D3	Corners, edges and openings
	D4	Installation

Once the influencing parameters had been defined, a structured damage classification system was developed to ensure homogeneous identification and codification of facade pathologies. The classification was based on the damage observed during fieldwork, the reviewed literature [2,11,31], and the criteria established in the UNE 41805-3 standard [32].

The identified damage types were grouped into four main categories according to the nature of the pathological process: physical damage, chemical damage, mechanical damage, and other singular damage. Physical damage includes moisture-related processes, surface soiling, and erosion phenomena. Chemical damage includes efflorescence, oxidation, corrosion, biodeterioration, and chemically induced erosion. Mechanical damage includes cracking, fissures, detachments, loss of cohesion, and mechanically induced erosion [33]. The final category includes anthropogenic or singular alterations, such as inappropriate interventions, odd elements, discoloration, graffiti, and mutilation.

Each damage type was assigned a specific code. This codification allowed the field observations to be transformed into analysable data and made it possible to compare damage frequency, spatial distribution, and relationships with influencing parameters. The use of a codified taxonomic system is essential for ensuring repeatability, reducing interpretative ambiguity, and enabling the statistical treatment of the information [34–36].

The proposed damage classification system is summarized in Table 2.

Table 2. Damage classification and coding system used for facade pathology assessment.

TYPES OF DAMAGE D		
	CODE	CONCEPT
D-P PHYSICAL NATURE		
2 Dirtiness	D-P1.1	Capillarity humidity
	D-P1.2	Infiltration humidity
	D-P1.3	Accidental humidity
	D-P2.1	Dirtiness due to deposit
	D-P2.2	Dirtiness from different washing
	D-P2.3	Dirtiness Staining from splash
	D-P2.4	Biological staining
3 Erosion	D-P3.1	Brick erosion
	D-P3.2	Erosion coating

Table 2. *Cont.*

TYPES OF DAMAGE D		
	CODE	CONCEPT
D-C CHEMICAL NATURE		
4 Efflorescence	D-C1.0	Efflorescence
5 Oxidation	D-C2.0	Oxidation and corrosion
6 Biodeterioration	D-C3.1	Biodeterioration_Mould lichen
	D-C3.2	Biodeterioration_Animal nitrite
	D-C3.3	Biodeterioration_Vegetation
3 Erosion	D-C4.1	Brick erosion
	D-C4.2	Erosion coating
D-M MECHANICAL NATURE		
7 Cracking	D-M1.1	Cracking structural movements
	D-M1.2	Cracking dilation and shrinkage
	D-M1.3	Cracking concrete
8 Fissure	D-M2.1	Fissure in the support
	D-M2.2	Fissure in the coating
9 Detachment	D-M3.1	Detachment cladding
	D-M3.2	Detachment coating
	D-M3.3	Detachment of the support material
	D-M3.4	Detachment painting
	D-M3.5	Loss of cohesion
3 Erosion	D-M4.1	Brick erosion
	D-M4.2	Erosion coating
D-O OTHER SINGULAR DAMAGE		
10 Other Damage	D-O5.1	Inappropriate interventions
	D-O5.2	Odd elements
	D-O5.3	Discolouration
	D-O5.4	Graffiti
	D-O5.5	Mutilation

Together, the codification of influencing parameters and the taxonomic classification of damage provided the basis for transforming the information obtained during visual inspection into structured data. This enabled the subsequent correlation between damage types, environmental exposure, building age, and affected facade units.

3.4. Standardized Inspection Sheets and Database Generation

The information collected during documentary research, visual inspection, photographic recording, and mapping was organised using standardized inspection sheets. These sheets constitute one of the central methodological tools of the proposed framework, since they ensure that all facades are analysed according to the same criteria and that the information is recorded in a homogeneous, comparable, and reproducible way.

Three complementary types of sheets were developed. The first sheet records the general data of the building and its exposure conditions, including location, construction

date, age category, height, orientation, distance from the sea, wind exposure, traffic intensity, street width, and other contextual variables. It also includes a general photograph of the facade and a georeferenced location map [11,13].

The second sheet contains the graphic mapping of the pathological condition of the facade. It represents the location and distribution of each identified damage type using a codified graphic system [37]. This sheet allows the spatial concentration of damage to be analysed and facilitates the identification of critical facade areas [3].

The third sheet records each recorded damage case in detail. It includes the damage code, damage type, affected construction unit, degree of deterioration, location, and detailed photographic documentation [2,38]. The same structure was applied to all analysed facades, allowing the creation of a systematic catalogue that can be expanded in future studies.

The structure of the three standardized inspection sheets is shown in Figure 3. This figure presents the three complementary levels of information used in the framework: general building and exposure data, graphic mapping of the pathological condition, and detailed damage records [37].

(a) GENERAL DATA

LOCATION	Phase 1	WIND EXPOSURE	Phase 1
DATE		TRAFFIC INTENSITY	
ANTIQUE		STREET WIDTH (M)	
BUILDING HEIGHT		HISTORICAL IRRIGATION DITCHES	
ORIENTATION			

Rectified image facade Phase 2

Location map Phase 1

TYPE OF FACADE

- Load-bearing facade
- Facade enclosure

TYPE OF FINISH

- Facing brick
- Continuous coating
- Lime plaster
- Cement mortar
- Masonry mortar
- Paint finish
- Cladding
- Natural stone cladding (NSC)
- Ceramic cladding (CC)
- Artificial stone cladding (ASC)

LOCATION OF THE DAMAGE

	1	2	3	4	5	6	7	8	9	10
Z ₁ Facade in contact with the ground										
Z ₂ Parapet on the roof										
Z ₃ Central area										
D ₁ Protruding elements										
D ₂ Balconies										
D ₃ Corners, edges, joints and openings										
D ₄ Installations										

(b) MAPPING

Image

Damage mapping

Phase 2

Legend:

- Dirtyness
- Decomposition of facing bricks
- Discoloration of facing bricks
- Efflorescence on facing bricks
- Paints blistering
- Loss of pointing
- Rust
- Loss of section of ornamental elements
- Cracks
- Broken tiles
- Improper elements
- Interventions
- Eroded edge on cornices
- Paints peeling
- Flaking of coating
- Vegetation
- Mutilation
- Discoloration
- Biological deterioration
- Detachment of cladding
- Humidity
- Graffiti
- Pitting
- Wooden elements - moisture
- Fissures

(c) DAMAGE -

LEVEL OF DETERIORATION

LEVEL 0

LEVEL 1 good 0% - 10%

LEVEL 2 slight deterioration 10% - 20%

LEVEL 3 large deterioration 20% - 45%

LEVEL 4 general deterioration > 45%

LOCATION OF THE DAMAGE

Z₁ Z₂ Z₃ D₁ D₂ D₃ D₄

Detail photography

Damage

Phase 2

DAMAGE -

LEVEL OF DETERIORATION

LEVEL 0

LEVEL 1 good 0% - 10%

LEVEL 2 slight deterioration 10% - 20%

LEVEL 3 large deterioration 20% - 45%

LEVEL 4 general deterioration > 45%

LOCATION OF THE DAMAGE

Z₁ Z₂ Z₃ D₁ D₂ D₃ D₄

Detail photography

Damage

Phase 2

COMMENTS

Figure 3. Structure of the standardized inspection sheets: (a) general building and exposure data, (b) facade damage mapping, and (c) individual damage record.

The standardized inspection sheets improve the repeatability of the inspection process, reduce subjectivity in data recording, and facilitate the scalability of the method. They also allow the framework to be transferred to other urban contexts since the standardized sheets maintain a common structure while enabling the variables relevant to each building and environment to be selected and interpreted according to the specific conditions of each case study. An example of the application of the standardized inspection sheets to one of the analysed buildings is shown in Figure 4. This example illustrates how documentary information, facade mapping, and individual damage records are integrated into a single structured diagnostic record.

Once the information had been recorded in the standardized inspection sheets, all data were digitized and incorporated into a structured database. The database was organised using codified variables, including building age, environmental exposure parameters, construction unit, damage type, and damage frequency.

This step completed the transition from visual and graphic documentation to structured analytical data. The use of codified variables made it possible to compare the information collected from different facades and to prepare the dataset for the subsequent statistical treatment and cluster analysis.

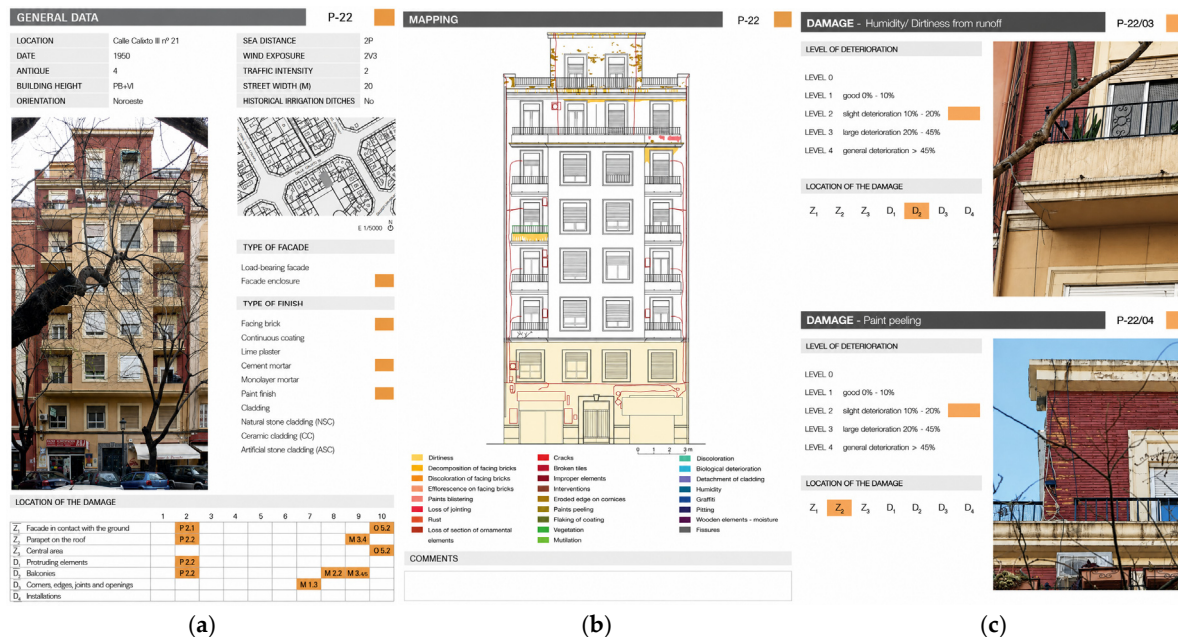


Figure 4. Example of completed standardized inspection sheets for one analysed building: (a) general data sheet, (b) facade damage mapping sheet, and (c) individual damage record sheet.

3.5. Statistical Treatment and Cluster Analysis

The use of a structured database enabled the statistical analysis of individual and combined variables. First, the frequency of each damage type was calculated in relation to the total number of identified cases. Second, the distribution of damage was analysed according to building age, orientation, distance from the sea, wind exposure, traffic intensity, and facade unit. Third, correlation tables and graphical representations were generated to identify recurrent patterns and critical combinations between damage type and influencing parameters.

This process transformed qualitative visual inspection data into quantitative evidence, allowing the diagnostic interpretation of facade pathologies to be supported by measurable results. The statistical analysis also provided the basis for identifying recurrent damage types, vulnerable facade areas, and possible relationships between damage occurrence and environmental or constructive factors.

In order to identify groups of damage types according to their frequency and diagnostic relevance, a K-means cluster analysis was applied to the dataset [2]. The analysis was performed on the frequency values of the damage types identified during the fieldwork.

The input matrix for the K-means analysis consisted of 33 observations, corresponding to the 33 damage types defined in the classification system, and one numerical variable: the total frequency of occurrence of each damage type in the database. Therefore, the clustering was not performed on a multivariable matrix including building age, environmental exposure, facade units, and damage types simultaneously, but on the standardized frequency values of each damage type. The purpose of the analysis was to obtain a reproducible and data-driven frequency hierarchy, rather than to define arbitrary thresholds between high-, moderate-, and low-frequency damage. Since the clustering was performed on a single numerical variable, multicollinearity among input variables was not applicable. Building

age, environmental exposure parameters, and facade construction units were analysed separately and were not included as input variables in the K-means procedure.

K-means was selected because the analysis aimed to obtain a small number of ordered and interpretable frequency groups. Density-based algorithms, such as Density-Based Spatial Clustering of Applications with Noise (DBSCAN), were considered less suitable because the objective was not to identify irregular density regions or noise points. Before applying the clustering algorithm, the frequency values were standardized using Z-score normalization. This transformation expresses the observations on a standardized scale with zero mean and unit variance before applying the clustering procedure. As shown in Equation (1), this process reduces the influence of scale differences during clustering.

$$z = \frac{(x - \mu)}{\sigma} \quad (1)$$

where z is the standardized value, x is the original frequency value, μ is the mean of the dataset and σ is the standard deviation.

The K-means algorithm partitions the dataset into K non-overlapping clusters by minimizing the within-cluster sum of squared Euclidean distances between each data point and the centroid of its assigned cluster, as expressed in Equation (2). Different cluster configurations were tested in order to determine the most appropriate number of clusters for the dataset.

$$\min_c \sum_{k=1}^k \sum_{x_i \in C_k} \|x_i - \mu_k\|^2 \quad (2)$$

where $C = \{C_1, C_2, \dots, C_k\}$ represents the set of clusters, k is the number of clusters, x_i is each data point assigned to cluster C_k , and μ_k is the centroid of cluster C_k . The objective of the K-means algorithm is to minimize the within-cluster sum of squared distances, so that data points assigned to the same cluster are as close as possible to their corresponding centroid.

The quality and interpretability of the resulting cluster configurations were evaluated using two complementary metrics: the Silhouette Score and the ratio between the between-cluster sum of squares and the total sum of squares (BSS/TSS). The Silhouette Score was used to assess the cohesion and separation of the clusters, while the BSS/TSS ratio was used to evaluate the proportion of total variance explained by the clustering solution. These metrics made it possible to balance statistical performance and diagnostic interpretability.

The BSS/TSS ratio was calculated according to Equation (3).

$$\frac{BSS}{TSS} = \frac{TSS - WSS}{TSS} \times 100 \quad (3)$$

where BSS is the between-cluster sum of squares, TSS is the total sum of squares and WSS is the within-cluster sum of squares.

$$s(i) = \frac{b(i) - a(i)}{\max(a(i), b(i))} \quad (4)$$

where $a(i)$ is the mean intra-cluster distance for data point i , and $b(i)$ is the lowest mean distance between data point i and the points assigned to the nearest neighboring cluster.

The clustering output was interpreted according to three frequency-based groups: high-frequency damage, moderate-frequency damage, and low-frequency damage. This classification provides a diagnostic tool for identifying the most recurrent damage patterns and for supporting maintenance planning. High-frequency damage types indicate recurrent issues that should be considered in preventive maintenance protocols and systematic monitoring strategies; moderate-frequency damage types represent recurrent degradation

processes associated with ordinary maintenance; and low-frequency damage types may reveal isolated, singular, or context-specific pathological conditions.

By incorporating cluster analysis into the framework, the methodology moves beyond descriptive cataloguing and provides a data-driven interpretation of facade pathology patterns. This reinforces the applicability of the proposed framework for diagnostic assessment, preventive maintenance, and prioritization of intervention strategies.

4. Results

The application of the proposed framework to the Valencia case study generated a structured dataset composed of 1600 damage cases identified on 168 facades. The results are presented in four complementary levels of analysis: first, the overall frequency of the identified damage types; second, the cluster-based classification of damage frequency; third, the relationship between damage occurrence and the influencing parameters; and fourth, the distribution of damage according to facade construction units.

4.1. Overall Frequency of Facade Damage

The first level of analysis aimed to identify the most recurrent pathological processes within the analysed facade sample. Figure 5 shows the number of cases recorded for each damage type according to the classification system defined in Table 2. The graphical representation was organized by damage category and coded according to the proposed taxonomy, allowing a direct comparison between the different types of facade pathologies.

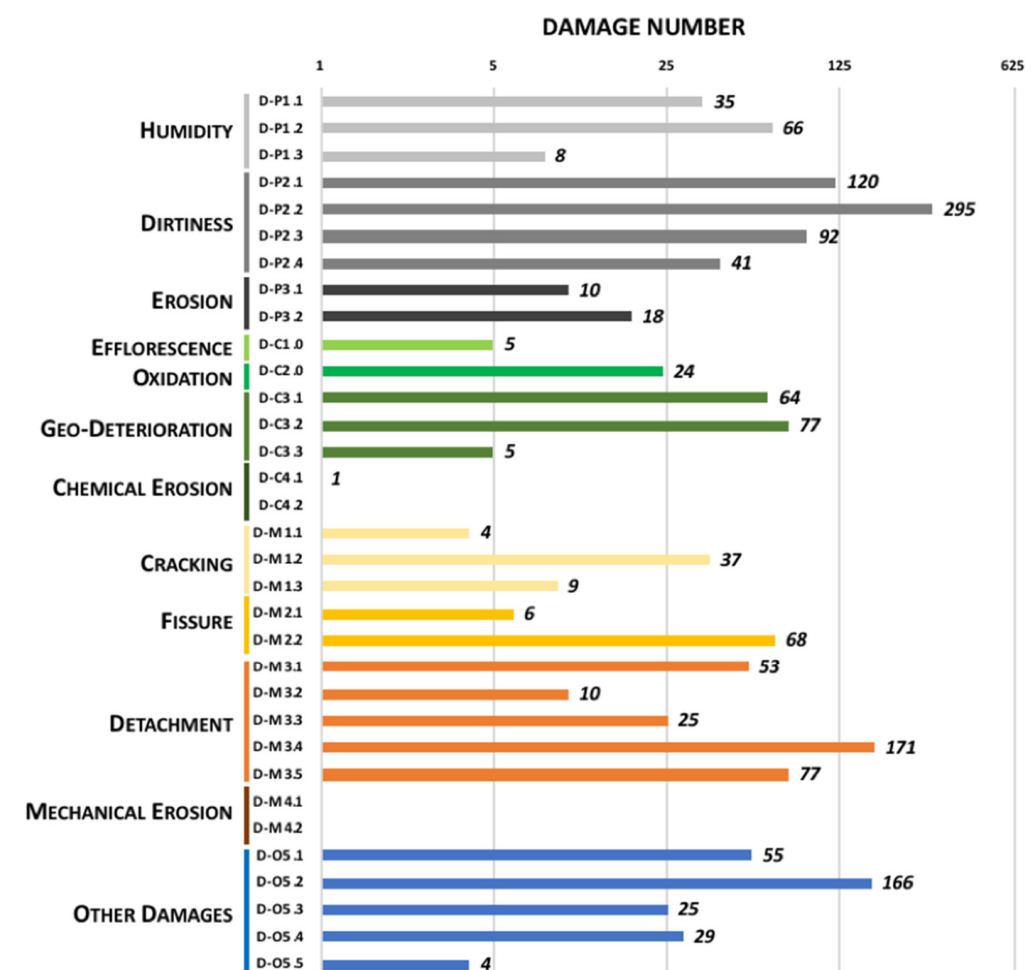


Figure 5. Number of damage cases by damage type in relation to the total number of damages identified in the analysed facades.

The results show that the most frequent damage type was soiling due to differential washing, with 295 cases, followed by paint detachment, with 171 cases, the presence of odd elements, with 166 cases, and soiling due to deposit, with 120 cases. These four damage types represent the most recurrent pathological conditions detected in the analysed facades.

When the results are interpreted by damage category, the percentages refer to the total number of recorded cases within each specific category. Infiltration humidity was the most common moisture-related pathology, accounting for 60.55% of the humidity cases, followed by capillarity humidity, with 32.11%. Within the soiling category, soiling due to differential washing represented 53.83% of the cases, followed by soiling due to deposit, with 21.89%, and splash staining, with 16.78%. In the biodeterioration category, the most frequent manifestations were animal nitrite deposits, with 52.74%, and mould and lichen, with 43.83%. Regarding detachments, paint detachment was the most frequent case, with 50.89%, followed by loss of cohesion, with 22.91%, and coating detachment, with 15.77%. In the case of fissures, cracks in the finishing material represented 91.89% of the detected cases. Finally, within the category of other singular damage, odd elements represented 59.49%, followed by inappropriate interventions, with 19.71%.

These results confirm the capacity of the proposed framework to record and classify a wide range of facade pathologies using a homogeneous coding system. The frequency distribution also provides a first diagnostic hierarchy, identifying the damage types that should be considered in preventive maintenance and inspection protocols.

4.2. Cluster-Based Classification of Damage Frequency

In order to move beyond descriptive frequency analysis, a K-means cluster analysis was applied to the dataset. The objective was to group the identified damage types according to their frequency of occurrence and to obtain a diagnostic classification capable of supporting the design of preventive inspection and maintenance protocols.

Different clustering configurations were evaluated for values of k ranging from 2 to 10. For each configuration, the Silhouette Score and the BSS/TSS ratio were calculated in order to assess both statistical performance and interpretability. Figure 6 shows the sensitivity analysis used to compare the different clustering solutions.

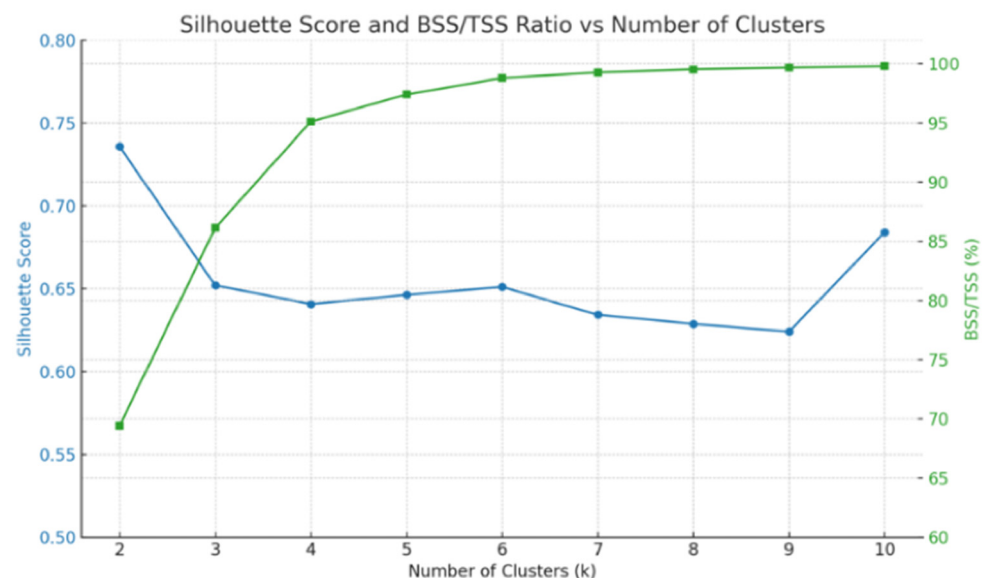


Figure 6. Evaluation of clustering performance according to the number of clusters. Silhouette Score and BSS/TSS ratio were used to assess the balance between cohesion, separation, variance explained, and interpretability.

The highest Silhouette Score was obtained for $k = 2$, with a value of 0.74, indicating strong cohesion and separation between clusters. However, this solution produced an overly simplified classification, broadly separating high-frequency damage types from the remaining cases. The three-cluster solution provided a better balance between statistical performance and diagnostic interpretability, with a Silhouette Score of 0.65 and a BSS/TSS ratio of 86.13%. Although configurations with higher values of k increased the explained variance, they generated micro-clusters that were less useful for diagnostic interpretation and maintenance decision-making.

For this reason, the $k = 3$ solution was retained as the most appropriate clustering configuration. This solution classified damage types into three groups: high-frequency damage, moderate-frequency damage, and low-frequency damage. Table 3 summarizes the diagnostic interpretation of each cluster.

Table 3. Diagnostic interpretation of the three frequency-based damage clusters.

Cluster	Frequency Group	Number of Damage Type	Mean Frequency	Standard Deviation	Mean Silhouette Coefficient
Cluster 1	High frequency damage	3	210.67	73.08	0.34
Cluster 0	Moderate frequency damage	9	74.67	20.78	0.60
Cluster 2	Low frequency damage	21	14.10	13.34	0.72

The cluster characterization identified three distinct frequency-based groups. Cluster 1 included three damage types—soiling due to differential washing, paint detachment, and odd elements—which presented the highest individual occurrence frequencies. Cluster 0 comprised nine damage types with moderate occurrence frequencies. Although this cluster accounted for the largest accumulated number of damage cases, this result is explained by the greater number of damage types included in the group. By contrast, Cluster 1 contained fewer damage types, but each of them showed a substantially higher individual frequency. Cluster 2 comprised 21 damage types with low occurrence frequencies. Therefore, the clustering should be interpreted according to the individual frequency of the damage types included in each group, rather than solely on the basis of the total number of cases accumulated by each cluster.

Figures 7 and 8 show the distribution of damage according to the retained cluster configuration, using complementary relative and absolute representations. Figure 7 presents the relative frequency of the damage groups, while Figure 8 shows the absolute number of recorded cases for each damage type according to its cluster assignment. The results indicate that Cluster 0 accounted for 42.0% of the total occurrences, followed by Cluster 1 with 39.5%, and Cluster 2 with 18.5%. This distribution confirms the predominance of moderate- and high-frequency damage types within the dataset and supports the usefulness of the clustering approach for identifying priority groups of facade pathologies.

The cluster-based classification provides a diagnostic reading of the dataset and reinforces the applicability of the proposed framework. Instead of treating all damage types as isolated observations, the method groups them according to their recurrence and potential maintenance relevance. However, this frequency-based hierarchy should be understood as a first diagnostic screening tool and should be complemented, in future applications, with additional criteria such as damage severity, extent, repair urgency, economic impact, and risk level.

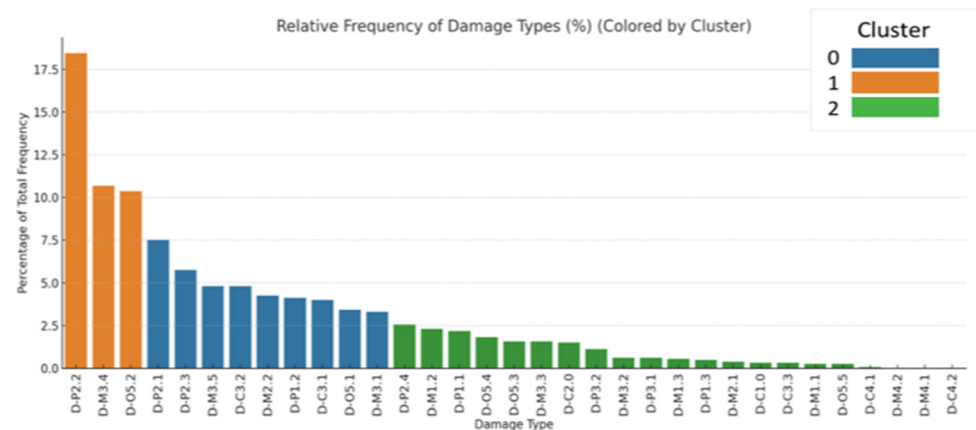


Figure 7. Relative frequency of damage types by cluster. The graph shows the percentage distribution of damage types according to the retained cluster configuration, allowing the relative weight of high-frequency, moderate-frequency, and low-frequency damage groups to be compared.

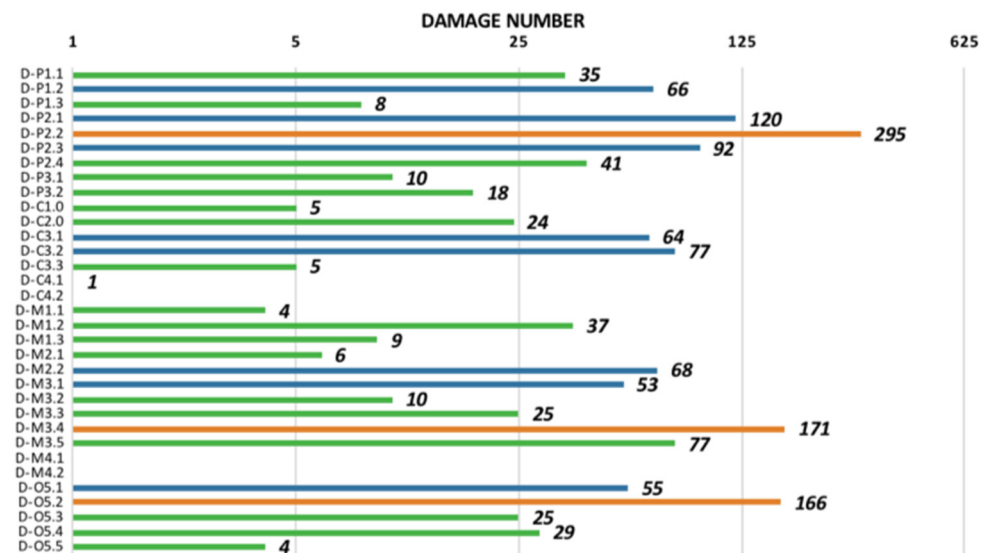


Figure 8. Number of damage cases by type and cluster assignment. The graph shows the absolute number of recorded damage cases for each damage type, coloured according to its corresponding cluster. This representation allows the frequency-based cluster classification to be interpreted in relation to the proposed damage taxonomy.

4.3. Relationship Between Damage Occurrence and Influencing Parameters

The second level of interpretation analysed the relationship between damage occurrence and the influencing parameters defined in the methodology. The objective was to identify how building age and environmental exposure conditions affected the distribution of facade pathologies.

Figure 9 shows the distribution of damage according to building construction period. The heatmap was used as the primary visualization tool because it allows variations in the number of recorded damage cases to be identified across the four construction-period categories and damage groups. The values shown in the heatmap correspond to the number of damage cases recorded in each category, not to the number or percentage of buildings.

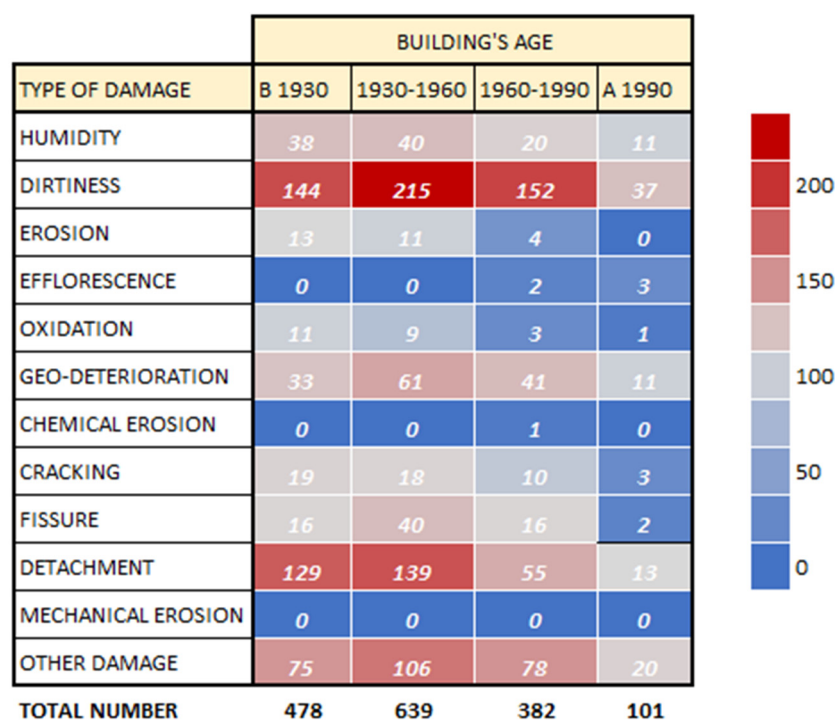


Figure 9. Distribution of damage according to building construction period. The heatmap shows the number of damage cases recorded in each construction-period category: B 1930, 1930–1960, 1960–1990, and A 1990.

Of the 1600 recorded damage cases, 478 were identified in buildings constructed before 1930, 639 in buildings constructed between 1930 and 1960, 382 in buildings constructed between 1960 and 1990, and 101 in buildings constructed after 1990. The highest number of damage cases was therefore observed in buildings constructed between 1930 and 1960.

The analysis of specific damage types according to building age shows that infiltration humidity was less frequent in the most recent and oldest groups, and more frequent in the intermediate age ranges. It was detected in 15% of buildings constructed after 1990, 26% of buildings constructed between 1960 and 1990, 41% of buildings constructed between 1930 and 1960, and 12% of buildings constructed before 1930.

In the case of soiling due to differential washing, its presence was relatively similar across the construction-period groups, with values of 83.3% in buildings constructed after 1990, 86% in buildings constructed between 1960 and 1990, and 83% in buildings constructed before 1960. By contrast, soiling due to deposit was more frequent in older construction periods, reaching 57% in buildings constructed before 1960, 32% in buildings constructed between 1960 and 1990, and 22% in buildings constructed after 1990.

Paint detachment showed a clearer relationship with construction period. It was detected in 33% of buildings constructed after 1990, 50% of buildings constructed between 1960 and 1990, and 63% of buildings constructed before 1960. This age-related trend was even more evident for the detachment of continuous cladding, which was observed in 5% of facades constructed between 1960 and 1990 and 36% of those constructed before 1960.

Figure 10 illustrates the relationship between selected damage types and the main influencing parameters, including building age, orientation, distance from the sea, wind exposure, and traffic intensity.

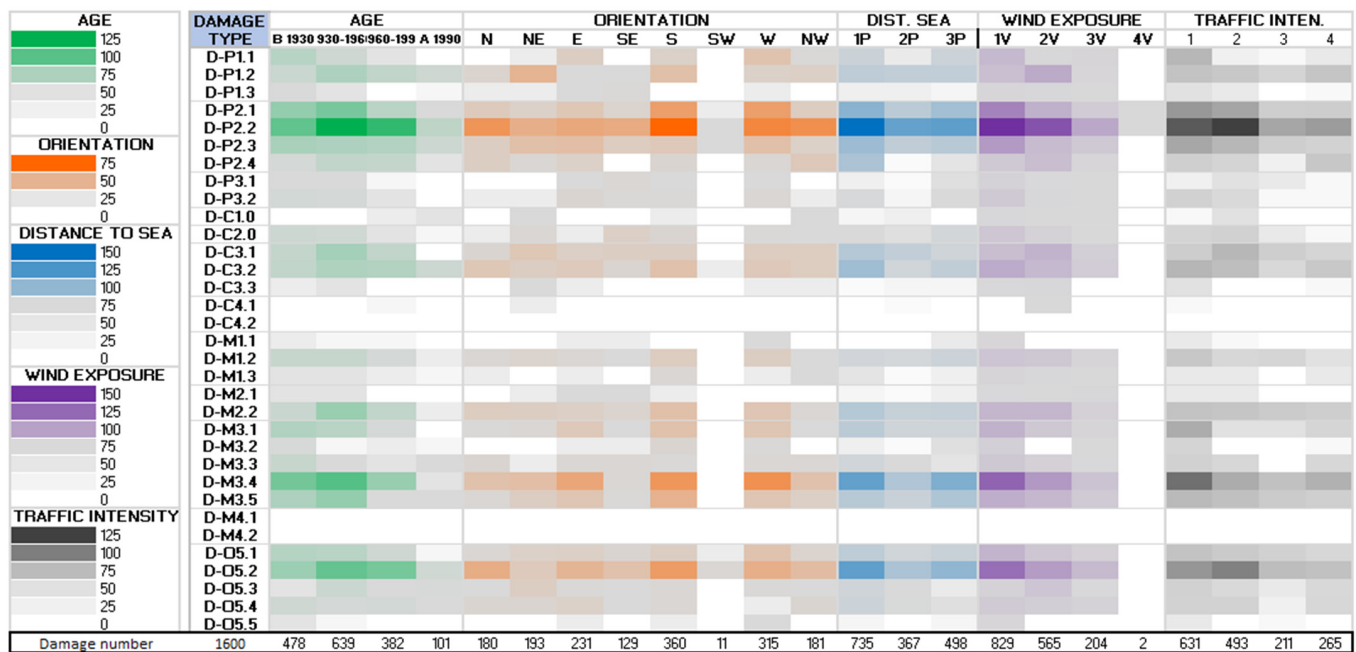


Figure 10. Number of recorded damage cases by damage type and influencing parameter: building age, orientation, distance from the sea, wind exposure, and traffic intensity. Percentages are calculated with respect to the total number of recorded damage cases ($n = 1600$).

Orientation also influenced the pathological condition of the analysed facades. In the Mediterranean coastal context of Valencia, facades facing northeast, east, and southeast showed the highest number of damage cases, with 553 cases, corresponding to 34.56% of the total. These were followed by southwest, west, and northwest orientations, with 507 cases, corresponding to 31.68%; south-facing facades, with 360 cases, corresponding to 22.5%; and north-facing facades, with 180 cases, corresponding to 11.25%.

Traffic intensity was particularly relevant in relation to soiling due to deposit and soiling due to differential washing. The streets with the highest traffic intensity presented the greatest number of damage cases: level 1 streets accounted for 631 cases, corresponding to 39.43%, and level 2 streets accounted for 493 cases, corresponding to 30.82%. Lower traffic levels showed a smaller number of damage cases, with 211 cases in level 3 streets and 265 cases in level 4 streets.

These results show that the proposed framework makes it possible to relate damage frequency not only to the type of pathology, but also to the environmental and urban conditions surrounding each facade. This reinforces its usefulness as a diagnostic tool for identifying exposure-related degradation patterns.

4.4. Damage Distribution According to Facade Construction Units

The third level of analysis focused on the spatial distribution of damage across the different facade construction units [31]. This analysis is essential for identifying critical points and for supporting preventive strategies in the design, construction, repair, and maintenance phases [3].

Figure 11 shows the number of damage cases recorded in each facade unit. The results indicate that the wall area near ground level was the most affected zone, with 499 cases, corresponding to 31.18% of the total. It was followed by balconies, with 293 cases, corresponding to 18.31%, and cornices or roof parapets, with 242 cases, corresponding to 15.12%. Corners, edges, and openings accounted for 210 cases, corresponding to 13.12%; overhangs accounted for 175 cases, corresponding to 10.93%; continuous wall surfaces

accounted for 146 cases, corresponding to 9.12%; and installations accounted for 35 cases, corresponding to 2.18%.

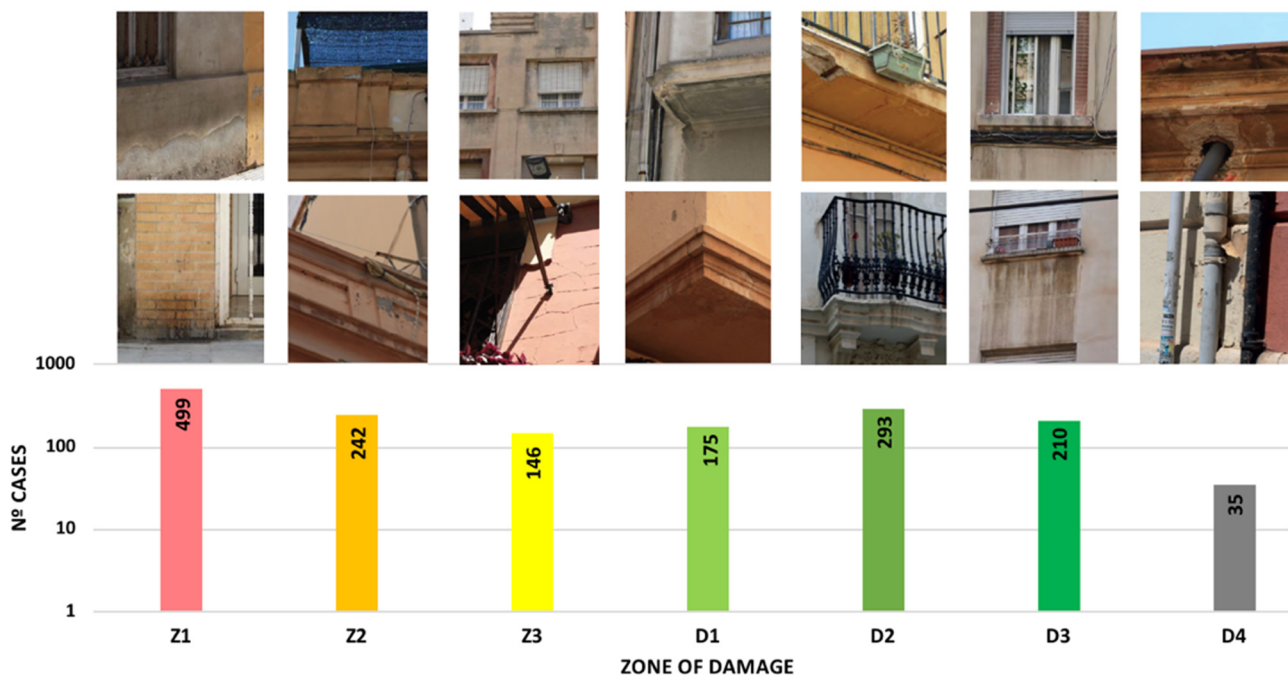


Figure 11. Number of damage cases according to facade construction unit.

Figure 12 presents a more detailed correlation between damage type and facade unit. The intensity of the colour assigned to each cell indicates the relative concentration of each damage type in the corresponding facade area. This representation makes it possible to identify which pathological processes are most strongly associated with specific construction units.

In the wall area near ground level, 499 cases were recorded. The most frequent damage types in this zone were splash staining, with 88 cases, corresponding to 5.50% of the total; animal nitrite biodeterioration, with 74 cases, corresponding to 4.62%; and paint detachment, with 64 cases, corresponding to 4.00%.

In cornices and roof parapets, 242 cases were recorded. The most significant damage type was soiling due to differential washing, with 72 cases, corresponding to 4.50% of the total. In the continuous wall area, 146 cases were recorded, with soiling due to deposits being the most recurrent damage type, with 24 cases, corresponding to 1.50%.

In the singular facade areas considered as critical points, 175 cases were recorded in overhangs, 293 in balconies, and 210 in corners, edges, and openings. These areas showed a recurrent presence of soiling due to differential washing, infiltration humidity, soiling due to deposits, paint detachment, and loss of cohesion.

The spatial distribution of damage confirms the diagnostic importance of considering facade construction units within the assessment framework. The results show that damage is not randomly distributed across the facade, but tends to concentrate in specific areas where exposure, material discontinuities, water runoff, geometry, and maintenance difficulties interact. This information is particularly useful for prioritizing inspections and defining targeted maintenance actions.

DAMAGE TYPE	ZONE OF DAMAGE						
	Z1	Z2	Z3	D1	D2	D3	D4
D-P1.1	34	1	0	0	0	0	0
D-P1.2	2	18	3	4	24	15	0
D-P1.3	0	0	0	0	1	1	6
D-P2.1	38	4	24	28	11	11	4
D-P2.2	1	72	0	69	90	61	2
D-P2.3	88	1	0	1	1	1	0
D-P2.4	0	16	0	7	14	4	0
D-P3.1	6	1	0	1	2	0	0
D-P3.2	3	2	0	5	7	1	0
D-C1.0	0	2	1	0	0	2	0
D-C2.0	0	4	0	0	13	5	2
D-C3.1	1	27	1	20	11	3	1
D-C3.2	74	0	0	0	1	2	0
D-C3.3	0	2	0	0	1	1	1
D-C4.1	0	1	0	0	0	0	0
D-C4.2	0	0	0	0	0	0	0
D-M1.1	0	1	1	0	0	2	0
D-M1.2	0	14	2	5	3	12	1
D-M1.3	1	1	0	0	6	1	0
D-M2.1	0	3	0	0	2	1	0
D-M2.2	4	9	10	7	16	20	2
D-M3.1	21	2	3	6	11	9	1
D-M3.2	5	0	2	1	0	2	0
D-M3.3	2	2	2	3	14	2	0
D-M3.4	64	28	10	13	34	13	9
D-M3.5	19	17	6	4	12	18	1
D-M4.1	0	0	0	0	0	0	0
D-M4.2	0	0	0	0	0	0	0
D-O5.1	12	8	6	1	9	15	4
D-O5.2	91	2	66	0	6	1	0
D-O5.3	3	3	7	0	4	7	1
D-O5.4	29	0	0	0	0	0	0
D-O5.5	1	1	2	0	0	0	0
TOTAL	499	242	146	175	293	210	35

Figure 12. Correlation between damage type and facade construction unit.

5. Discussion

The results obtained from the Valencia case study demonstrate the applicability of the proposed framework for the systematic assessment of facade pathologies in urban buildings. As presented in Section 4, the inspection of 168 facades and the identification, classification, mapping, and codification of 1600 damage cases show that the methodology is capable of transforming visual observations into structured and quantifiable data. The frequency analysis in Section 4.1, the cluster-based classification in Section 4.2, the analysis of influencing parameters in Section 4.3, and the construction-unit distribution in Section 4.4 provide complementary levels of interpretation. Together, these results confirm the usefulness of the framework not only for identifying frequent damage types, but also for relating them to building age, environmental exposure, and affected facade units.

The most frequent damage types identified in Section 4.1 were soiling due to differential washing, paint detachment, odd elements, and soiling due to deposits. This hierarchy, shown in Figure 5, provides the first diagnostic reading of the dataset and identifies the damage types that require greater attention in preventive maintenance strategies. These results are consistent with previous studies that highlight the relevance of surface degradation, staining, detachment, and material ageing in the pathological evolution of facades. However, the main contribution of this research does not lie exclusively in the identification of these recurrent damage types, but in the development of a standardized procedure that allows them to be recorded, classified, spatially located, and statistically interpreted within a single diagnostic workflow.

The recurrent presence of soiling, staining, detachment, cracking, and moisture-related damage in the Valencia sample is broadly consistent with pathological processes reported

in previous Portuguese and Brazilian studies on rendered facades, natural stone claddings, and ceramic external wall claddings [10,12,15,32]. However, a direct quantitative comparison of damage frequencies is not appropriate because these studies differ in their objectives, materials, sampling criteria, damage taxonomies, and units of analysis. The comparison is therefore limited to the identification of common degradation mechanisms, such as water runoff, particle deposition, solar and thermal exposure, material discontinuities, and maintenance conditions. In Valencia, the observed predominance of differential-washing and deposit-related soiling may additionally be interpreted in relation to the Mediterranean coastal environment, wind exposure, traffic intensity, street geometry, and facade projections.

This interpretation is supported by the parameter-based results presented in Section 4.3, where the distribution of damage was analysed in relation to building age, orientation, distance from the sea, wind exposure, and traffic intensity. The construction period was included as one of the parameters used to analyse the distribution of damage within the sample. The highest number of recorded damage cases corresponded to buildings constructed between 1930 and 1960. However, the specific influence of the materials, construction techniques, and maintenance strategies associated with each construction period falls outside the scope of the present article and will be addressed in subsequent research.

Previous studies have addressed facade degradation from different methodological perspectives. Gaspar and de Brito analysed the sensitivity of external mortar renders to defects and developed degradation indicators for specific facade systems [37]. Flores-Colen et al. focused on stains in rendered facades and their relationship with diagnosis and maintenance techniques [12]. Silva, de Brito, and Gaspar proposed service-life prediction methodologies and models for specific cladding systems, such as rendered facades and natural stone wall claddings [13,14,39]. Similarly, Serralheiro et al. developed a methodology for service-life prediction of architectural concrete facades [11]. These studies have made relevant contributions to the understanding of facade degradation, particularly in relation to specific materials, construction systems, or service-life estimation.

Compared with these approaches, the framework proposed in this study adopts a broader and more integrated perspective. Rather than focusing on a single cladding material or facade system, the methodology was applied to a heterogeneous urban sample including different facade typologies, construction periods, and exposure conditions. This approach makes it possible to analyse the facade as a complex envelope system composed of different construction units and exposed to multiple degradation agents. In this sense, the proposed framework complements material-specific degradation models by providing a systematic procedure for large-scale urban facade assessment.

Other studies have analysed building envelope pathologies using large datasets derived from user complaints, insurance claims, or legal proceedings. Carretero-Ayuso et al., for example, examined recurrent damage combinations in building envelopes based on reported cases that had led to legal processes [2]. These approaches are valuable for identifying conflict-prone defects and recurrent construction failures. Nevertheless, they are conditioned by the nature of the data source, since only reported or legally recognized damage cases are included. In contrast, the present framework is based on direct visual inspection of complete street samples, avoiding the exclusive reliance on reported damage and allowing the identification of visible pathologies regardless of whether they have generated complaints or administrative records [40].

The proposed methodology also differs from conventional visual survey approaches because the inspection is not limited to qualitative observation. Visual information is progressively converted into codified and analysable data through photographic recording, facade mapping, standardized inspection sheets, and database generation. This sequence

improves the traceability of the diagnostic process and reduces the subjectivity associated with isolated visual assessments. The use of standardized inspection sheets is particularly relevant, as it ensures that all facades are recorded according to the same criteria and that the information can be compared across buildings and urban contexts.

The incorporation of cluster analysis further strengthens the methodological contribution of the study. As shown in Section 4.2 and Table 3, the K-means classification provides a data-driven interpretation of damage frequency, grouping the identified pathologies into high-frequency, moderate-frequency, and low-frequency categories. This approach allows the results to move beyond descriptive cataloguing and supports a diagnostic hierarchy that can inform preventive inspection and maintenance protocols. In particular, the high-frequency group identifies recurrent damage types that may require systematic monitoring and preventive strategies [41], whereas low-frequency damage types may indicate singular situations, localised defects, or context-specific degradation processes. Therefore, the clustering procedure adds an operational layer to the framework by linking statistical interpretation with maintenance decision-making.

The relationship between damage occurrence and facade construction units, presented in Section 4.4 and Figures 11 and 12, also confirms the importance of spatial codification. The concentration of damage in specific areas [3], such as the wall near ground level, balconies, cornices, roof parapets, openings, and edges, shows that facade degradation is not randomly distributed. These critical points are strongly influenced by geometry, exposure, water runoff, construction discontinuities, material interfaces, and maintenance accessibility. Identifying these vulnerable areas is essential for improving design criteria, planning inspection routines, and defining targeted intervention strategies.

From a practical perspective, the proposed framework can support technicians, building owners, planners, and public administrations in the management of urban building stocks. The structured database generated from the inspection sheets provides an evidence-based basis for identifying recurrent damage patterns, designing preventive maintenance protocols, and planning preventive conservation strategies. In this sense, the methodology may contribute to improving existing building assessment procedures, particularly in contexts where facade inspections are still based on general observations or insufficiently detailed regulatory reports.

The proposed framework should not be understood as an exhaustive procedure for inspecting every facade in an entire city. The framework is transferable because its standardized sheets record a common set of variables. This allows users to select and interpret data based on each building's specific characteristics and context. The sheets already include variables such as building age and height, facade orientation, distance from the sea, wind exposure, traffic intensity, street width, construction characteristics, and the facade unit in which each damage case is located. Therefore, applying the framework to different climatic zones or building types does not require modifying its methodological structure, damage taxonomy, or facade-unit classification. In marine environments, for example, distance from the sea, orientation, and wind exposure may be particularly relevant. In high-rise buildings, height, facade position, and exposure conditions may acquire greater significance. In historic buildings, age, construction characteristics, materials, and previous interventions may be especially informative. The standardized structure therefore remains unchanged, while the selection and interpretation of the recorded variables are contextualized for each case study. Despite these contributions, several limitations should be acknowledged. First, the methodology is based primarily on visual inspection and therefore focuses on visible surface damage. Hidden defects, internal material degradation, or structural anomalies that cannot be detected visually may require complementary diagnostic techniques, such as thermography, ultrasonic testing, moisture measurements,

or other non-destructive testing methods. Second, although standardized inspection sheets, predefined damage categories, photographic documentation, and team verification were used to improve consistency, some degree of expert judgement remains inherent in visual assessment. Third, the framework was validated in the specific urban and environmental context of Valencia. Future studies in other geographical areas are therefore necessary to assess its applicability under different climatic, urban, and construction conditions. Fourth, the cluster analysis was based on damage frequency and did not include weighting according to severity, extent, repair urgency, economic impact, or risk level. Therefore, the resulting hierarchy should be interpreted as a preliminary diagnostic classification rather than as a complete maintenance decision model. Finally, the frequency-based clustering was derived from the Valencia dataset and has not yet been externally validated. Its broader generalizability should therefore be assessed using independent datasets from other urban and climatic contexts.

Overall, the results confirm that the proposed framework provides a reproducible and transferable methodology for facade pathology assessment. Its main value lies in the integration of visual inspection, damage taxonomy, spatial mapping, standardized data recording, database generation, statistical analysis, and cluster-based interpretation. This integrated approach makes it possible to connect field diagnosis with maintenance planning and to generate structured knowledge that can be expanded, compared, and applied in other urban environments.

6. Conclusions

This research developed and validated a standardized framework for the inspection, classification, mapping, codification, and statistical analysis of facade pathologies in urban buildings. The proposed methodology integrates documentary research, systematic visual inspection, photographic recording, damage taxonomy, facade mapping, standardized inspection sheets, database generation, statistical treatment, and cluster-based interpretation within a single reproducible diagnostic workflow.

The framework was validated through an urban case study in Valencia, Spain, where 168 facades were inspected and 1600 damage cases were identified, classified, mapped, and incorporated into a structured database. The results demonstrate that the proposed procedure enables homogeneous data collection and makes it possible to transform qualitative visual observations into quantitative and comparable information.

Applying this methodology identified the most recurrent damage types. These include soiling from differential washing, paint detachment, odd elements, and soiling from deposits. The analysis also showed that damage occurrence is related to building age, environmental exposure conditions, and specific facade construction units. In particular, areas such as the wall near ground level, balconies, cornices, roof parapets, openings, and edges were identified as critical points where damage tends to concentrate.

The incorporation of K-means cluster analysis provided an additional diagnostic layer by grouping damage types according to their frequency of occurrence. The classification into high-frequency, moderate-frequency, and low-frequency damage groups supports the design of inspection, preventive maintenance strategies, and intervention planning. This confirms the usefulness of data-driven methods for improving the interpretation of facade pathology datasets.

The main contribution of this research is not limited to the identification of facade damage in a specific urban context but lies in the development of a standardized and reproducible assessment framework. The methodology can be transferred to other urban environments because the standardized inspection sheets allow each building and its context to be characterized while maintaining a common data-recording structure. In each

application, the variables most relevant to the case can be selected and interpreted according to the local climatic, environmental, urban, and construction conditions. In this sense, the proposed framework can support technicians, researchers, building owners, and public administrations in evidence-based facade diagnosis and preventive conservation planning.

Future research should expand the database to other cities and climatic contexts, incorporate additional variables such as damage severity, extent, repair urgency, and economic impact, and combine visual inspection with complementary non-destructive testing techniques where necessary. The development of a digital or open-access platform based on the proposed framework could further improve data updating, professional accessibility, and decision-making in the management of urban building stocks.

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Abbreviations

The following abbreviations are used in this manuscript:

BIM	Building Information Modelling
BSS	Between-cluster Sum of Squares
CAD	Computer-Aided Design
DBSCAN	Density-Based Spatial Clustering of Applications with Noise
NDT	Non-Destructive Techniques
TSS	Total Sum of Squares
UAV	Unmanned Aerial Vehicle
UNE	Una Norma Española
WSS	Within-Cluster Sum of Squares

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