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Critical Analysis about Emerging Technologies for Building's Façade Inspection

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Abstract: The diagnosis of the building's façades pathology is extremely important to support rational and technically informed decisions regarding maintenance and rehabilitation actions. With a reliable diagnosis, the probable causes of the anomalies can be correctly identified, and the correction measures adopted can be more compatible with the existing elements, promoting the durability of the façades. Visual inspection is the most common approach to identify anomalies in a building's façade and, in many cases, this technique is sufficient to support the decision to intervene. However, the pathological phenomenon is complex, and the anomalies observed may indicate the presence of other defects, or some anomalies may not be visible in a simple visual observation. This study intends to discuss the application of emerging technologies on the diagnosis and anamneses of building's façade, in order to automatise the collection of reliable on-site data and, thus, reduce the uncertainty of the diagnosis. The use of these techniques can help existing inspection methodologies, already tested, based mainly on the visual assessment of the buildings' elements degradation condition.

Keywords: diagnosis; advanced technologies; façade; claddings; building inspections

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1. Introduction

In recent years, the international scientific community has gained more attention in the field of inspection, diagnosis, maintenance, and rehabilitation of buildings. The maintenance and rehabilitation are considered key factors in buildings' sustainability since these interventions increase the service life of buildings [1]. Inspection and diagnosis of building elements are a very important task to support decision and efficiency of building façade maintenance from the building facades [2,3]. However, there is some uncertainty during these procedures associated with the observation of the degradation phenomenon and the diagnosis process [4].

Collecting information from fieldwork about natural degradation of building elements, is an alternative to laboratory tests like artificial weathering cycles. The fieldwork survey could be very useful to compare with the laboratory tests, since it allows identifying the real-life effects of weathering on the performance of building elements, considering the simultaneous effects of different climatic degradation agents [5–8]. In facades, the degradation condition could be assessed from visual inspections, which involve a non-destructive inspection method. This type of analysis is a natural way to judge the service life of these constructive elements since the maintenance decisions are made based on this type of assessment [9,10]. In that context, several works have been developed, concerning the degradation of buildings and their elements, based on visual inspections [11–14]. These studies can be complemented by some expedient tools, like binoculars to get a closer observation, a tape measure to obtain some dimensional information, a crack with a ruler, and a colour system sample [2]. Other additional diagnosis techniques can also be applied, whether they are non-destructive or destructive techniques. However, visual inspections intend to be easily applicable in practice and without high costs.

Visual inspection is the first method used to evaluate the condition of many infrastructures and buildings [15–17]. Despite the limitations of visual inspections, this method can immediately provide general information about the condition of the building elements [9,18]. This task is usually done by an expert, which performs a survey looking for the damage in order to determine the areas that need intervention. The results of that visual inspection are reliable when dealing with easily visible parts of the façade. However, usually it is not easy, for a surveyor, to analyse the top of the façade or assess anomalies that are in deeper locations without appropriate means of access, and with unfavourable weather conditions. In that context, a reliable and rapid assessment of the defect areas on a large façade may be a difficult work for the surveyor [4,19–23]. Moreover, a visual inspection is highly dependent on the surveyor's expertise [2,24]. Hence, a visual assessment can be considered subjective, human-dependent, time-consuming, and can have low accuracy in defects' measurements in certain situations [16,24]. However, based on the knowledge regarding the condition of the building's elements, is crucial for the adoption of adequate maintenance strategies and it is fundamental for life cycle analysis, considering the economic and environmental costs of the building components over their life cycle [23,25,26].

The limitations of visual inspections motivated the use of systemized alternatives such as remote sensing for mapping the defective areas on a surface of building façades [19,22]. In recent years, the interest about advanced technologies to automate the inspection of building façades has emerged. Some studies have been developed in the field of building's façade inspection, mainly in cultural heritage buildings, by focusing on building an energy audit [21,23,27–31]. Novel technologies for a reality capture have been applied, mainly terrestrial laser scanning, photogrammetry, infrared thermography, photogrammetry, and drones. The application of these technologies can improve the traditional survey, producing more objective results in a faster way [23,32]. They could automate and improve the visual inspection, reducing the subjectivity associated with the inspector's survey [17,24]. Nevertheless, automation as a way to detect and measure a given defect is still a great challenge, which needs several technologies combined for accurately mapping all the anomalies that can occur in a given building component. More research is needed to put into practice these technologies to support the facades' inspections.

Most of these studies only focus on a single technology. Different defects could require different technologies to support and automate building's facades' diagnosis. In this sense, this study intends to discuss the suitability of these advanced technologies to automate a visual assessment during field inspection and the new trends for inspection of buildings' facades with a focus in current buildings. Furthermore, the most suitable technology to support the diagnosis of different kinds of defects is identified. These technologies can bring some automation for the inspection and diagnosis of buildings and their components, reducing the inspection time in the field, avoiding several visits to the building's location (because all the necessary information is not collected during the first time), and producing more reliable information about the anomalies present in the component under analysis.

2. Materials and Methods

In order to discuss the most suitable technologies to automate a visual assessment of several defects in buildings' facades, this research follows a specific methodology. To better understand the needs of advanced technologies, two case studies are presented, to illustrate the application of a building inspection system, based on a visual assessment of the degrading building components. In this inspection system, the parameters involved in the calculation of the facades' degradation condition are explained in detail and some improvements are suggested. In addition, to illustrate some uncertainty associated with the visual inspection, the same 47 natural stone claddings are inspected by two surveyors in different moments. Then, an extensive literature review, with about 50 references, is performed to systematise the technologies able to automate the visual façade inspection in buildings. In the end, the suitability of previous technologies is presented, in the sense of an automated visual assessment, according to different defects present in facades. Some recommendations are made in this topic. In the next sections, these topics will be developed and discussed in detail.

3. Global Inspection System for the Buildings' Envelope Elements: 2 Case Studies

The adoption of adequate maintenance strategies is the most efficient way of increasing the durability of buildings and their elements. However, an adequate intervention needs an accurate and reliable diagnosis of the defects and possible causes. Each building is unique and presents different types of defects. Nevertheless, certain patterns can be identified when analysing a large sample of buildings. A systematic analysis of the data collected during the building inspections can provide a reliable database for a guidance to prevent the occurrence of defects and to repair the existing ones. For these reasons, several inspection systems have been developed by different authors. Ferraz [1] presented and discussed 10 building pathology databases, developed between 1982 and 2013. More recently, Lee [33] proposed an inspection methodology to introduce information about building defects into BIM (Building Information Model). Bortolini and Forcada [26] proposed a building inspection system for the assessment of whole building performance [34]. Gonçalves [35] analysed the existing methods of inspection and diagnosis for ancient buildings, based on visual inspections.

In fact, it is almost consensual that building inspection benefits from the standardisation of inspection and diagnosis procedures [36,37]. The adoption of inspection systems helps surveyors to have harmonised procedures, which makes inspection reports more consistent and simpler to understand [2,3,38].

In recent years, different methodologies for the inspection and diagnosis of non-structural elements of the building envelope have been established, in order to create a reliable database and systemise procedures for the on-site assessment of defects [39–41]. Moreover, several studies in service life prediction methodologies have been developed, with the aim to evaluate when it is necessary to intervene based on the element's degradation condition assessment [42,43].

Under the SLP for BMS (Service Life Prediction for a risk-based Building Management System) research project, a global inspection system was developed [44]. This system embraces 12 building elements, namely: external claddings of pitched roofs, flat roofs, adhesive ceramic tiling, natural stone claddings, wood floorings, door and window frames, epoxy resin floorings, vinyl and linoleum floorings, wall renders, external thermal insulation composite systems (ETICS), painted façades, and architectural concrete surfaces. The unification of these partial inspection systems implied the harmonisation of the classification of defects, probable causes, diagnosis methods, and repair techniques in a single system. This global inspection system intends to provide a solid basis for surveyors to inspect the building envelope through standardisation of procedures [3,34].

This global system is based on visual and physical scales to characterize the building envelope elements during the inspections. Gaspar & de Brito [45] begin this work with the development of a qualitative scale, based on the assessment of the physical and visual degradation of rendered façades, analysed during a fieldwork survey, which can be associated with a quantitative index. This describes the global performance of the façades [42]. This numerical index, called severity of degradation (S_w), expresses the global degradation of a given façade through the ratio between a weighted degraded area and a reference area, equivalent to the total cladding with the highest possible level of degradation (Equation (1)). The weighted degraded area is a product of the façade area affected by different groups of anomalies with a weighted factor related to the severity of each anomaly detected (k_n)

and a weighted factor associated with relative weight of each anomaly on the overall degradation of façade ($k_{a,n}$).

$$S_w = \frac{\sum(A_n \times k_n \times k_{a,n})}{A \times \sum(k_{max})} \quad (1)$$

where S_w is a severity of degradation of the cladding, expressed as a percentage. k_n is the multiplying factor of anomaly n, as a function of their degradation level, within the range K = {0, 1, 2, 3, 4}. $k_{a,n}$ is a weighting factor corresponding to the relative weight of the anomaly detected. An is the area of cladding affected by an anomaly n. A is the total area of the cladding, and k_{max} is the multiplying factor corresponding to the highest degradation level of the cladding [42]. This methodology was developed to external renders and applied to the building elements previously mentioned.

To discuss the reliability of this severity of the degradation (S_w) index, two case studies are presented in this paper: (i) a continuous element (a rendered wall) and (ii) a discontinuous element (a natural stone cladding). These two claddings represent different challenges in the calculation of severity of the degradation index, which will be presented later. Figure 1 describes a rendered wall inspected according to the global inspection system. The case study is a building located in Tavira, Algarve (South of Portugal). The façade is oriented toward the west and present an average level of protection against the wind and rain. In terms of environmental factors, the inspected building is located at less than 3 km from the sea in a rural environment and exposed to normal conditions of air temperature and relative humidity. The total area of the facade analysed is 105.52 m^2 and the render is 10 years old.

Figure 1. First case study: rendered façade (data sourced from Reference [46]).

Table 1 presents the defects in the rendered façade (Figure 1) observed during the visual inspection carried out during the fieldwork survey. The surveyor recorded the area of rendering affected by each group of defects (A_n). The degradation condition level of each defect found (k_n), according to its condition (taking into account the classification of defects proposed in Table 2), and the factor corresponding to the relative weight of each defect in the overall degradation of the façade ($k_{a,n}$), according to Table 3. In summary, Table 1 presents the weighted degraded area ($A_n \times k_n \times k_{a,n}$), taking into account the defects observed. In order to calculate the severity of the degradation (S_w) index of this cladding, Equations (2) and (3) are used.

Table 1. Identification of anomalies observed in a rendered façade, after an inspection.

Defects		A_n (%)	A_n (m^2)	k_n(-)	$k_{a,n}$ (-)	$A_n \times k_n \times k_{a,n}$ (m^2)
Stains, A_{stains}	Condition B	2.5	2.63	1	0.67	1.762
	Condition C	4.2	4.41	2	0.67	5.909
	Condition D	3.1	3.26	3	0.67	6.553
	Condition E	-	-	4	0.67	-
Cracking, $A_{cracking}$	Condition B	-	-	1	1.00	-
	Condition C	3.3	3.47	2	1.00	6.940
	Condition D	1.8	1.91	3	1.00	5.730
	Condition E	4.1	4.30	4	1.50	25.800
Loss of adhesion, $A_{adhesion}$	Condition B	-	-	1	1.50	-
	Condition C	-	-	2	1.50	-
	Condition D	0.8	0.85	3	1.50	3.825
	Condition E	-	-	4	1.50	-

Table 2. Classification of the degradation condition of rendered facades to the level of the defect (k_n) [1].

Degradation Condition	Physical and Visual Assessment	Illustrative Example
Condition A (k_n = 0)	Complete mortar surface with no deterioration, with surface even and uniform. No visible cracking or cracking ≤ 0.1 mm. Uniform colour and no dirt. No detachment of elements.	
Condition B (k_n = 1)	Non-uniform mortar surface with capillary cracking (0.1 to 0.25 mm). Slight stains in localized areas, mainly dirt.	
Condition C (k_n = 2)	Non-uniform mortar surface with likelihood of hollow localized areas determined by percussion, but no signs of detachment. Small cracking (0.25 to 1.0 mm) in localized areas. Changes in the general colour of the surface with a potential presence of microorganisms.	
Condition D (k_n = 3)	Mortar with localized detachments or perforations, revealing a hollow sound by percussion. Detachments only in the socle. Easily visible cracking (1 to 2 mm). Dark stains of damp and dirt, often with microorganisms and algae.	
Condition E (k_n = 4)	Incomplete mortar surface due to detachments and falling of mortar patches. Wide or extensive cracking (≥ 2 mm). Very dark stains of damp and dirt, often with microorganisms and algae.	

[1] Data sourced from References [42,47].

Table 3. Weighted factor for render facades ($k_{a,n}$) [1].

Degradation Condition	Stains	Cracking	Loss of Adhesion
Condition A	0.00	0.00	0.00
Condition B	0.67	1.00	1.50
Condition C	0.67	1.00	1.50
Condition D	0.67	1.00	1.50
Condition E	0.67 *	1.50	1.50

* 1.00 in the situations of occurrence of ice / thaw cycle. [1] Data sourced from References [42,47].

In Equation (3), the calculation of the severity of degradation (S_w) for this case study is presented. The result is a S_w index of 13.39%, which means a slight degradation of rendered façade, according to Table 4.

$$S_w = \frac{\sum(A_{stains} \times k_n \times k_{a,n}) + \sum\left(A_{cracking} \times k_n \times k_{a,n}\right) + \sum(A_{adhesion} \times k_n \times k_{a,n})}{A \times k_{max.}} \quad (2)$$

$$S_w = \frac{\overbrace{1.762 + 5.909 + 6.553}^{A_{stains}} + \overbrace{6.940 + 5.730 + 25.800}^{A_{cracking}} + \overbrace{3.825}^{A_{adhesion}}}{105.52 \times 4} \times 100 = \frac{56.519}{422.08} \times 100 = 13.39\% \quad (3)$$

Table 4. Correspondence between the degradation condition and severity of degradation of rendered facades [1].

Degradation Condition	Severity of Degradation, S_w
Condition A (no degradation)	$S_w \leq 1\%$
Condition B (good)	$1\% < S_w \leq 5\%$
Condition C (slight degradation)	$5\% < S_w \leq 15\%$
Condition D (moderate degradation)	$15\% < S_w \leq 30\%$
Condition E (generalized degradation)	$S_w \geq 30\%$

[1] data sourced from References [42,47].

Figure 2 describes another case study, a natural stone cladding, directly adhered to the substrate, which was inspected using the global inspection system. This case study refers to a building located in Parque das Nações, Lisbon (Centre of Portugal). The façade is oriented toward the east and presents an average level of protection against the combined action of wind and rain. In terms of environmental factors, the inspected building is located at less than 3 km from the sea, in an urban environment, and exposed to unfavourable conditions of air temperature and relative humidity. The total area of the facade analysed is 75 m^2 and the natural stone cladding is 12 years old.

The defects observed in the natural stone cladding inspected (Figure 2) are synthetized in Table 5. The surveyor recorded the area of natural stone affected by each group of the defect (A_n): A_v—visual anomalies, A_j—joint anomalies, A_f—bond-to-substrate anomalies, and A_i—loss-of-integrity anomalies. The degradation condition level of each defect found (k_n) and the factor corresponding to the relative weight of each defect on the overall degradation of façade ($k_{a,n}$) are assigned according to the condition classification in Table 6. In summary, Table 5 presents the weighted degraded area ($A_n \times k_n \times k_{a,n}$) in order to calculate the severity of the degradation (S_w) index (Equations (4) and (5)).

Figure 2. Second case study: natural stone cladding.

Table 5. Identification of anomalies observed in natural stone cladding after performing façade inspection.

Defects		A_n (%)	A_n (m^2)	k_n(-)	$k_{a,n}$ (-)	$A_n \times k_n \times k_{a,n}$ (m^2)
Visual, A_v	Condition B	-	-	1	0.13	-
	Condition C	40.3	30.24	2	0.13	7.862
	Condition D	-	-	1	0.13	-
	Condition E	-	-	1	0.13	-
In joints, A_j	Condition B	-	-	1	-	-
	Condition C *	20	15	2	0.25	7.500
	Condition C **	10	7.50	2	1	15.000
	Condition D	-	-	3	-	-
	Condition E	-	-	4	-	-
Bound-to-substrate, A_f	Condition B	-	-	1	1.20	-
	Condition C	10	7.50	2	1.20	18.000
	Condition D	-	-	3	1.20	-
	Condition E	-	-	4	1.20	-
Loss-of-integrity, A_i	Condition B	-	-	1	1	-
	Condition C	10.8	8.10	2	1	16.200
	Condition D	20	15	3	1	45.000
	Condition E	-	-	4	1	-

* joint anomalies only with material degradation. ** joint anomalies with material loss—open joint.

Table 6. Classification system for natural stone claddings [1].

Degradation Condition	Anomalies		$k_{a,n}$	% Area of NSC Affected	Severity of Degradation (%)
A (k_n = 0)	No visible degradation		-	-	$S_w \leq 1$
B (k_n = 1)	Visual or surface degradation anomalies	Surface dirt	0.13	>10	$1 < S_w \leq 8$
		Moisture stains/localised stains/colour change	0.13	≤15	
		Flatness deficiencies	0.13	≤10	
	Loss-of-integrity anomalies	Material degradation * ≤ 1% plate thickness	1.00	-	
		Material degradation * ≤ 10% plate thickness Cracking width ≤ 1 mm	1.00	≤20	

Table 6. *Cont.*

Degradation Condition	Anomalies		$k_{a,n}$	% Area of NSC Affected	Severity of Degradation (%)
C (k_n = 2)	Visual or surface degradation anomalies	Moisture stains/localised stains/colour change	0.13	>15	$8 < S_w \leq 20$
		Moss, lichen, algae growth/parasitic vegetation/efflorescence	0.13	≤30	
		Flatness deficiencies	0.13	>10 and ≤50	
	Joint anomalies	Joint material degradation	0.25	≤30	
		Material loss-open joint	1.00	≤10	
	Bond-to-substrate anomalies	Scaling of stone near the edges Partial loss of stone material	1.20	≤20	
	Loss-of-integrity anomalies	Material degradation * ≤ 10% plate thickness Cracking width ≤ 1 mm	1.00	>20	
		Material degradation * > 10% and ≤ 30% plate thickness Cracking width > 1 mm and ≤ 5 mm	1.00	≤20	
		Fracture	1.00	≤5	
D (k_n = 3)	Visual or surface degradation anomalies	Moss, lichen, algae growth/parasitic vegetation/efflorescence	0.13	>30	$20 < S_w \leq 45$
		Flatness deficiencies	0.13	>50	
	Joint anomalies	Joint material degradation	0.25	>30	
		Material loss-open joint	1.00	>10	
	Bond-to-substrate anomalies	Scaling of stone near the edges Partial loss of stone material	1.20	>20	
		Loss of adherence	1.20	≤10	
	Loss-of-integrity anomalies	Material degradation * > 10% and ≤ 30% plate thicknessCracking width > 1 mm and ≤ 5 mm	1.00	>20	
		Material degradation * > 30% plate thickness Cracking width > 5 mm	1.00	≤20	
		Fracture	1.00	>5 and ≤10	
E (k_n = 4)	Bond-to-substrate anomalies	Loss of adherence	1.20	>10	$S_w > 45$
	Loss-of-integrity anomalies	Material degradation * > 30% plate thickness Cracking width > 5 mm	1.00	>20	
		Fracture	1.00	>10	

* Material degradation is meant to be every anomaly that involves loss of volume of the stone material. [1] data sourced from Reference [42].

In Equation (5), the calculation of the severity of degradation (S_w) of the second case study is presented. The result is a S_w index of 10.43%, which means a slight degradation (Condition C) of the natural stone cladding analysed, according to Table 7.

$$S_w = \frac{\sum(A_v \times k_n \times k_{a,n}) + \sum(A_j \times k_n \times k_{a,n}) + \sum\left(A_f \times k_n \times k_{a,n}\right) + \sum(A_i \times k_n \times k_{a,n})}{A \times k_{max.}} \quad (4)$$

$$S_w = \frac{\overbrace{7.862}^{A_v} + \overbrace{7.5 + 15}^{A_j} + \overbrace{18}^{A_f} + \overbrace{16.2 + 45}^{A_i}}{75 \times 14} \times 100 = \frac{109.562}{1050} \times 100 = 10.43\% \quad (5)$$

Table 7. Correspondence between the degradation condition and the severity of degradation of natural stone claddings [1].

Degradation Condition	Severity of Degradation, S_w
Condition A (no degradation)	$S_w \leq 1\%$
Condition B (good)	$1\% < S_w \leq 8\%$
Condition C (slight degradation)	$8\% < S_w \leq 20\%$
Condition D (moderate degradation)	$20\% < S_w \leq 45\%$
Condition E (generalized degradation)	$S_w \geq 45\%$

[1] data sourced from Reference [48].

In these two case studies, the visual inspection was aided by a crack ruler to measure the thickness of the cracks and a tape measure to get dimensions to support the quantification of defected areas (A_n) in the stone cladding and rendered façades. These procedures strongly influence the parameters used to calculate the severity of the degradation (S_w) index. Furthermore, these inspections are a time-consuming process. Only the natural stone cladding in the bottom wall was analysed, and, in some areas, a ladder was needed to evaluate the defects present in the façade in more detail at a higher level. These examples confirm that the reliability of this global inspection system depends on the accuracy of the data collection, and it is intrinsically related to the surveyor's expertise and the inspection conditions. Some automation in data collection could help to obtain more reliable and standardised results and reduce the acquisition time of the data.

4. The Uncertainty Associated with the Building Inspection Based on Fieldwork

The global inspection system adopted for the inspection of the facades previously analysed, is based only on the visual assessment of the components, thus, encompassing some uncertainty on the quantification of the degraded areas, as discussed previously. To illustrate this issue, Table 8 shows the results of the inspections carried out on the same 47 natural stone claddings by two surveyors. The two surveyors perform these inspections as part of their masters' thesis in civil engineering [40,48]. After processing the collected data acquired by different methodologies, the two inspectors obtained different results in some façades, leading to a variation between 0% to 2.23% in the severity of the degradation index—S_w (variations %), as shown in Table 8. This could be related to some differences in the way data is collected by the surveyor, since they have different goals, which results in slightly different approaches, and the subjectivity associated with visual inspection is due to the assessment of each surveyor. Neto developed her work in the inspection and diagnosis of natural stone cladding [40] and Silva in a field of service life prediction of natural stone cladding [48]. In this sense, Neto [40] only identified the anomalies observed, and did not estimate all the areas affected by each anomaly, while Silva [48] estimated the areas affected by each defect in order to obtain the severity of the degradation index—S_w.

Table 8. The results obtained by two surveyors for the same 47 case studies of facades with natural stone cladding [1].

ID (from Neto, 2008)	S_w (Neto, 2008)	S_w (Silva, 2009)	S_w (Neto, 2008)/ S_w (Silva, 2009)	ΔS_w
Ed. A.1	2.1%	2.1%	1.00	0.00%
Ed. Q.2	1.8%	1.8%	1.00	0.00%
Ed. R.3	1.9%	1.9%	1.00	0.00%
Ed. T.2	2.1%	2.1%	1.00	0.00%
Ed. BB.4	0.6%	0.6%	1.00	0.00%
Ed. BB.5	1.1%	1.1%	1.00	0.00%
Ed. I.1	2.0%	2.0%	0.98	0.03%
Ed. H.3	1.6%	1.5%	1.03	0.05%
Ed. E.2	2.1%	2.0%	1.05	0.10%
Ed. F.2	1.1%	1.2%	0.87	0.16%
Ed. E.1	2.1%	1.9%	1.11	0.21%
Ed. I.3	1.3%	1.1%	1.20	0.21%
Ed. R.2	2.1%	1.9%	1.11	0.21%
Ed. F.1	1.1%	1.4%	0.79	0.29%
Ed. P.2	2.0%	1.7%	1.19	0.32%
Ed. Q.1	1.7%	1.4%	1.23	0.32%
Ed. BB.6	2.4%	2.7%	0.88	0.32%
Ed. I.2	4.3%	3.9%	1.10	0.40%
Ed. R.1	2.1%	1.7%	1.23	0.40%
Ed. Z.2	1.8%	2.3%	0.81	0.43%
Ed. Z.1	1.1%	1.5%	0.71	0.43%
Ed. T.3	0.8%	1.3%	0.63	0.47%
Ed. Z.3	2.1%	2.7%	0.80	0.54%
Ed. O.1	4.1%	3.5%	1.16	0.56%
Ed. K.4	3.0%	2.4%	1.28	0.66%
Ed. H.1	1.2%	0.5%	2.26	0.68%
Ed. T.1	1.5%	2.2%	0.68	0.70%
Ed. G.1	2.1%	2.8%	0.73	0.77%
Ed. D.3	0.9%	0.1%	11.58	0.78%
Ed. S.1	2.1%	3.0%	0.72	0.83%
Ed. K.3	2.0%	2.9%	0.70	0.85%
Ed. Q.3	2.0%	2.8%	0.70	0.86%
Ed. B.1	1.9%	1.0%	2.00	0.96%
Ed. CC.2	1.8%	2.7%	0.64	0.96%
Ed. KK.1	3.4%	2.3%	1.49	1.13%
Ed. AA.3	10.7%	9.5%	1.13	1.21%
Ed. U.1	4.5%	3.3%	1.38	1.23%
Ed. H.2	2.3%	1.0%	2.36	1.31%
Ed. AA.2	10.8%	9.3%	1.16	1.50%
Ed. D.2	2.0%	0.4%	4.85	1.55%
Ed. O.3	0.3%	1.9%	0.17	1.57%
Ed. K.1	3.3%	1.6%	1.99	1.63%
Ed. U.3	3.4%	1.7%	1.98	1.70%
Ed. D.1	2.0%	0.1%	14.22	1.81%
Ed. J.2	3.4%	1.5%	2.29	1.93%
Ed. K.2	2.7%	0.6%	4.20	2.06%
Ed. AA.1	10.7%	8.5%	1.26	2.23%

[1] data sourced from Neto [40] and Silva [48].

The differences between the results are associated with the type of information collected for severity of the degradation index calculation, to the gap in time between inspections and some limitations related to the visual survey, like weather conditions at the inspection moment (e.g., the incidence of solar radiation in the wall can mask some defects). The subjectivity associated with the inspector assessment is related to difficulties in assessment, mapping, and measurements of the defective areas in elevated areas of the building facades. Furthermore, the deviations between the values obtained by the two surveyors seem acceptable, given the subjectivity inherent to the visual inspection. However, other techniques could be applied to automate the inspection of facades, in order to reduce the subjectivity inherent in the visual inspection. Technologies like 3D laser scanning, infrared thermography, photogrammetry, digital image processing, and drones could provide some automation in collecting geometric and photographic data. These techniques intended to overcome some limitations in assessing and measuring the defects areas while improving the evaluation of the degradation condition through the severity of a degradation index (S_w).

5. Emerging Technologies to Automate Visual Building's Façade Inspection

In this section, some advanced technologies to automate a building facade inspection are summarized and discussed. To overcome some limitations in assessing and measuring the defects areas, previously shown in Sections 3 and 4, some technologies were selected to collect geometric and photographic data. The technologies analysed in this study are the most addressed in the literature [16,21,23,24,27–32,49,50]: 3D laser scanning, infrared thermography, photogrammetry, digital image processing, and drones. Each technology is presented succinctly, with the main focus of automate mapping and quantifying the defects observed in building facades. Some advantages and disadvantages are presented, intending to analyse and select the suitability technologies to complement and improve a visual assessment of building facades.

5.1. 3D Laser Scanning (TLS)

Terrestrial laser scanning (TLS) is a process that records a 3D digital image within a determined radius from the location of the laser scanner, through infrared light. The result are 3D point clouds of the objects surface. The use of this technique has grown in cultural heritage and historic preservation projects, mainly because their rapid, wide-ranging, and non-invasive method of documentation, which proved to be cost-effective when compared to traditional techniques. This technique is considered one of the best solutions for 3D digitalization of cultural heritage assets [51–53]. With TLS, it is possible to detect some defects as surface delamination, cracks, displacements, and deflections in walls [20,54]. This technology also allows measuring the defects with the acquired information into a Computer Aided Design (CAD) system [23]. The accuracy and details of the recording depend on the scanner specifications and the distance to the scanned object [23,54]. The mapping technique using a 3D laser scan allows a better prediction of replacement cost of wall surfaces through the location of the defects. Another advantage of this technique is the ability to document large areas at ground level, thus, avoiding the scaffolding costs and creating a safer environment for the surveyors [51].

However, the laser scanner has some drawbacks in collect data from hidden or unreachable surface areas from the ground, like capture points in tall buildings. In a historic urban context, with narrow streets, this technique does not provide good results [55]. Moreover, the equipment and software acquisition can be expensive with equipment prices around 30,000 euros [23,56,57].

However, the use of TLS aids to overcome the complexity in accessing some parts of buildings and the unfavourable lighting conditions, like shaded and lighted areas, because it is independent of solar lighting [23,51,52]. This technology generates coordinates of millions of points in reflecting surfaces, providing a rapid geometric representation of objects [19,23]. It provides a geometrical data with high resolution and accuracy, but usually the radiometric data is not useful to defects mapping, like stains, due to the sensors' limitations [23,29,55]. In that context, several authors [19,55,56] have done research combining TLS with other technologies like digital image processing, photogrammetry, and infrared thermography. Therefore, this approach brings some automation in mapping and measuring some defects in facades, as delamination as well as loss of adhesion and cracks (with some limitation in crack width) in a more accurate and detailed way.

5.2. Infrared Thermography (IRT)

Infrared thermography (IRT) is a non-destructive technique that has been applied in buildings inspection as an important diagnostic tool [37,58]. The principle is based on the measurement of the radiant thermal energy distribution, which is emitted from an object. The thermal energy is measured by an infrared camera [59]. This technology has been used to detected surface defects such as moisture, air leakage in the walls, detachment, and cracks in some type of claddings [37,58,60–65]. Thermography can detect anomalies with surface temperature variations. Methodologies combining infrared thermal images with TLS was performed and showed good results to identify anomalies on masonry walls [66]. Other authors [67,68] combines infrared thermography with photogrammetry techniques, intending to obtain thermographic information where it is possible to measure the defects on the image.

Despite the innumerable capabilities of this technology, there is some limitations related to the significant cost of infrared cameras with high resolution. However, there is a low-cost camera with costs around 500 euros [69]. Thermography is highly dependent on climatic conditions, components of a surrounding natural and built environment, building orientation and shape, surface roughness/texture/colour, and camera settings [58,70]. The façade should not be exposed to wetting, frosting, or direct solar radiation in the acquisition phase. In addition, this technique is significantly dependent on the expertise of the operator [71]. However, this technique could be an upgrade for damage detection in visual inspection with a capability of mapping moisture stains, detachment, loss of adhesion, and cracks, particularly when there is no access to the facade. IRT combined with photogrammetry techniques and TLS could also provide measures of mapped defects.

5.3. Photogrammetry and Remote Sensing (PRS)

The International Society of Photogrammetry and Remote Sensing define photogrammetry and remote sensing (PRS) as "the art, science, and technology of obtaining reliable information from noncontact imaging and other sensor systems about the earth and its environment, and other physical objects and processes through recording, measuring, analysing, and representation" [72]. PRS is a technique capable of determining 3D geometry of physical objects by analysing and measuring 2D photographs. It is divided in aerial and terrestrial photogrammetry. In aerial locations, images are acquired from an aircraft providing topographic maps. In terrestrial photogrammetry, images are acquired near the object and provide dimensional information about the object. In case of the object size and distance camera-to-object of less than 100 m, the technique is defined as close-range photogrammetry [73].

This technique could be applied, through a digital camera, in facades to obtain ortho-images, where, afterward, it is possible to measure the defects [74]. However, several authors have been combining PRS with other technologies, like TLS. With this arrangement, they provide good geometric and radiometric information, so it is possible to measure defects on façade [74,75]. Other authors combine image processing with PRS to automatic crack monitoring [56] and measure defects through the image in building façades [76]. One advantage of PRS is the cost, around 150 euros for the software, assuming there is a computer [77], typically lower than TLS (30,000 euros) [68].

5.4. Digital Image Processing (DIP)

Digital image processing is a technique to extract information from the images with several applications in engineering and architecture. This technique requires the use of software to perform image processing on digital images. There are two main areas of application, which is a low level that involves the improvement of pictorial information for human interpretation and a high level for the processing of scene data for autonomous machine perception, to give the system the ability to interpret and understand an image [78]. More specifically, low-level processing contains the image acquisition, image compression, a pre-processing method for noise filtering, edge extraction, and image sharpening. It also contains a high-level, useful mathematical method, such as neural networks, fuzzy logic, pattern recognition, and artificial intelligence [27,78].

This technique has been implemented in multiple areas such medicine, automation, security, and defence [79]. In recent years, this technique has been adopted in the architecture field for identifying different materials and defects such as in stone masonry facades. This work is based on image processing software, which contains algorithms capable of classifying the stone anomalies [79]. At this stage of image processing, more accuracy is needed. DIP has been used to detect and quantify defects in tiling work [78,80]. Thus, DIP is capable of measuring defective areas and increase the reliability of visual inspection [78], detecting cracks in building facades [81].

However, some image processing limitations are related to image acquisition, the cladding appearance, the camera distance, and position, and with a light condition at the inspection moment. Those factors can affect the image captured and cause some inaccuracies in the defects' detection [78].

5.5. Drones (UAV)

The use and development of drones has its origins in the military field in the middle of the century XIX. Since 2010, the scenery changed with the falling prices and increasing ease operation [70]. The advances in programming and autopilot systems, the miniaturization of components, such as gyros and GPS units, made the machines smaller, cheaper, and easier to fly [49]. Currently, drones or more formally known as Unmanned Aerial Vehicles (UAV), have high popularity and the technology has got a maturity level that makes it more user-friendly and inexpensive. It is possible to purchase a good UAV for prices around 1700 euros [82]. In the construction industry, the use of these devices can contribute to reduce the time of tasks, like monitoring construction activities and inspection of buildings, increase the quality of the work, improve safety standards, and reduce costs [83]. Building pathology and diagnosis can be done with drones faster than conventional methods, more safely, in some circumstances [49]. UAV can use coupled cameras to capture HD images and videos or infrared cameras and 3D laser scanners to identify damages and cracking in building facades [84,85]. UAV can fly in inaccessible areas without risk for the operator, like higher facades in tall buildings, or between buildings in narrow streets. The speed at which the survey can be performed in the field is also an advantage of this technology [49,86].

Some disadvantages are related to the quality of images and videos obtained, which can be influenced by light conditions and inspection distances to elements in some cases. The load of a different type of camera, the meteorological conditions, and physical barriers (e.g., trees near the façades) could also be a limitation for this technique [49]. The battery duration remains a big challenge to be solved with the best flight times around 30 min [82]. Additionally, the use of this technology must follow the country regulation [81].

UAV can be used with an infrared thermal camera. As a result of technological advances, the infrared sensors became smaller and lighter, which enabled their use by drones [70]. A geometric and photographic survey is also possible with a drone with a kinetic sensor installed. This solution is characterized as low-cost among others, which is capable of generating 3D models [87]. UAV with coupled cameras are particularly useful in visual inspection and are capable of improving the assessment of some defects, such as cracks and stains.

6. Critical Analysis for Inspection and Diagnosis of Facades Elements

In this section, the suitability of previous technologies presented to automate visual assessment of building facades is discussed. The aim of using these technologies is to collect more reliable data during fieldwork. The key improvement of the global inspection system relies on the calculation of the severity of degradation index (S_w), which evaluates the condition state of facade in real exposure conditions, based on visual inspections, as mentioned in Section 3. Consequently, there are several technologies capable of bringing some automation in the visual inspection, as mentioned in Section 5. However, the measurement of defective areas in facades is still a big challenge, as discussed in this section.

As previously shown in Section 4, the calculation of severity of the degradation index (S_w), in a global inspection system, could be improved if the collected data is more accurate and independent of the surveyor expertise as well as visual inspection conditions. Thus, advanced technologies can help in this context. The selected technique must be able to map the defects and mainly measure with an adequate accuracy (or with a known margin of error) the area affected by each anomaly type (e.g., cracks, detachments, and stains). With that purpose, in Table 9, a critical analysis of emerging technologies (selected in Section 5) is presented to map and measure defect areas in building facades, based on the accuracy of field data collection and based on the importance of this data for the calculation of the severity degradation index (S_w).

Table 9. Critical assessment of emerging technologies to measure defect areas in facades, according to the nature of defects.

		Emerging Technologies				
		TLS	**DIP**	**UAV**	**IRT**	**PRS**
Technical Features	**Mapping stains**	Only suitable with other technologies (−)	Suitable (+)	Suitable (+)	Only suitable for some stains (−)	Suitable (+)
	Mapping cracking	Suitable (+)	Suitable (+)	Suitable (+)	Only suitable for some cracking (−)	Suitable (+)
	Mapping loss of adhesion	Suitable, in case of façade geometry change (−)	Unsuitable, if there is no image change (−)	Unsuitable, if there is no image change (−)	Suitable (+)	Unsuitable, if there is no image change (−)
	Measure the crack thickness	Suitable (+)	Suitable (+)	Only suitable combined with other technologies (−)	Unsuitable (−)	Suitable (+)
	Quantify defect area	Only suitable combined with other technologies (−)	Suitable (+)	Only suitable combined with other technologies (−)	Only suitable combined with other technologies (−)	Suitable (+)
	Survey in tall buildings	Unsuitable, with acquisition from the ground (−)	Unsuitable, with acquisition from the ground (−)	Suitable (+)	Unsuitable, with acquisition from the ground (−)	Unsuitable, with acquisition from the ground (−)
	Access to the facade surface	Unsuitable, with narrow streets around (−)	Only suitable if image acquisition is done by drone (−)	Suitable (+)	Unsuitable, with narrow streets around (−)	Unsuitable, with narrow streets around (−)
	Weather conditions	Independent (+)	Dependent (−)	Dependent (−)	Dependent (−)	Dependent (−)

* Unsuitable (−). Suitable (+).

With the purpose of mapping stains in facades, all technologies are useful, except 3D laser scanning (TLS) because it could not produce colour information useful for mapping the defects [55]. Infrared thermography (IRT) is advisable for mapping claddings with loss of adhesion, cracking, and stains with moisture or another defect due to thermal gradients [61]. The measurement of crack thickness could be supported by TLS or photogrammetry (PRS) combined with digital image processing (DIP) for width around 0.2 mm. However, a high resolution camera is needed to get a good result [20,56,73]. To quantify defect area in facades, PRS and DIP are advisable. With the first technique, it is possible to measure over the image. In DIP, the defect areas can be obtained through several image processing techniques, supported by a software, for the operation to convert the pixel in the distance [56].

There are some parameters associated with the nature of inspection that also influence the selection of the best technology. For surveying high buildings and facade surfaces with difficult accessibility, like narrow streets, drones (UAV) are the more advisable technology. As presented before, the weather conditions significantly influence the technology capacity to map and quantify defects in facades, like windy conditions, presence of obstacles (e.g., trees), or solar radiation in facades [49,70]. In this sense, TLS could be a useful technique in these conditions, with the limitations presented before.

As discussed, several technologies should be used to improve the calculation of the severity of the degradation index (S_w), according to the type of defects in the building facades and the nature of the inspection. This aim can be achieved through better mapping and measure of each type of defect.

7. Conclusions

Visual inspection remains a very important tool for the assessment of the physical and visual condition of buildings' facades. However, there is some uncertainty associated with this analysis, namely in the quantification of defect areas, as shown in Sections 3 and 4.

This study intends to present some recommendations to automate the inspection process to reduce the uncertainty related with the visual assessment, namely reducing the subjectivity related to the inspector in assessing, mapping, and measuring the defects in building facades. In this sense, the use of new technologies can help significantly in the assessment of the degradation condition of claddings and, consequently, increase the reliability of an in-service diagnosis.

From the emerging technologies analysed, each one has different advantages and limitations, according to the literature. In short, this study reveals that there is no suitable technology for all types of defects. To quantify the degradation in facades through mapping and measuring defects, the technologies that are revealed to be more advisable were photogrammetry and digital image processing. These techniques are the most suitable for mapping defects, measuring the crack thickness, and quantifying defect areas. However, for mapping defects related to loss of adhesion, infrared thermography is more advisable and can show a hidden defect.

When parameters related to the nature of inspection action are considered, like the weather condition or the incidence of solar radiation in the façade, 3D laser scanning could be the best technology to overcome these limitations. In tall buildings and with difficult access to the surface façade, drones are recommended. Taking into account the type of defects in the building facade and the nature of inspection, these technologies are capable of automating the visual inspection, producing a more reliable and accurate diagnosis about the degradation condition of facades. Further analyses are needed concerning the real application of these technologies, evaluating the accuracy of the detection of the anomalies observed, and the reliability of estimating the severity of the degradation index (S_w), based on the information collected through these techniques.

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