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To cite this article: L M Acosta *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **222** 012027

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Exploring Technological Alternatives to the Visual Inspection Method in the Built Environment

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Abstract. Buildings show symptoms and suffer injuries or failures that demand efficient approaches and sustainable solutions in order to maintain or improve their condition. In previous studies, the authors of this paper proposed a network methodology which stores and analyzes information on the degradation of the built environment in different cities, based on a visual inspection methodology for data collection. The demand for accurate information analysis of facades, along with the inspection time for each facade, creates a need for new information collecting techniques. Therefore, this article aims to evaluate technological equipment incorporated in the traditional inspection methods that can work as a complement to achieve better and more advanced results. For this, an experiment was carried out in the city of Brno, Czech Republic, where five building facades in the city center were analyzed in order to qualify and validate a mobile georeferenced scanner, static georeferenced scanner and thermographic camera equipment for potential incorporation into the current inspection method. Quantitative and qualitative analyses are included, together with some of the capabilities and potential uses of these technological resources for an improvement in the network methodology.

1. Introduction

The research motivation for this paper arises from the necessity of conserving buildings through maintenance in order to fulfill general sustainability requirements, as well as to achieve a continuous revaluation and increase of their lifetime. The advantages of this conservation can be derived from the information in the built heritage in order to prevent degradation and waste of materials in the demolition and construction of a new real estate. An appropriate maintenance, together with refurbishment works adapted to the buildings' needs, allow the buildings to exceed the life cycle for which they were originally conceived. Therefore, this study is focused on the perspective of the urban front, i.e. the facade, which is determined by its construction and material elements. To achieve this objective, it will be necessary to use traditional experiments as well as high-performance graphic capture devices that allow to study different possibilities of data collection and analysis.



Traditional inspection based on direct observation by the inspector of the object has been the basis of BRAIN project (Building Research Analysis and Information Network) by Gibert (2016) [1] in recent years. This process is carried out through a series of inspections over a period of time, recorded and stored in databases composed of two datasheets: a first sheet identifies the buildings and a second sheet collects information concerning their facades and the level of degradation observed at the time of the inspection. However, this method relies on the individual inspectors responsible for the data collection (to inspect the facade in person, to observe and to determine the parameters that compose it, and to identify and classify the injuries). This raises the question of whether there is any way to make the methodology more efficient and to reduce the variability of results among the individual inspectors.

The exploration of alternative means for data collection and diagnosis of injuries is a challenging field that should be considered according to the interests and scope of the BRAIN methodology. The main objective of this research is to evaluate potential improvements in data collection and analysis through the use of high-performance graphic capture devices (high definition cameras, drones, lidar, scanners, etc.) provided within the framework of collaboration with the research line of Environment and Geo (Geotechnics and Geodesy) Applied Technological Research (EGAR) by the Advanced Materials, Structures and Technologies Laboratory (AdMaS) at Brno University of Technology (BUT). In order to conduct the analysis, an experiment was carried out in the city center of Brno, where five building facades were analyzed. The first part of the paper introduces the individual technological alternatives used in the experiment (Section 1), as well as the identification of the built environment in which the experiment was carried out (Section 2). The second part (Sections 3 and 4) compares and validates the qualitative results obtained by using the equipment after its use in several inspections in order to qualify each equipment for possible incorporation into the current inspection method.

2. An exploration of technological resources

The monitoring or constant inspection is considered one of the most important administrative areas in the realization of construction projects, to guarantee the quality of the final result. Emelianov et al. (2014) [2] states that laser scanning and photogrammetry can be used for the inspection and detection of defects, which can be valuable in matters of preventive maintenance. Researchers place special emphasis on how facades and structures, according to their material composition, can be affected by certain climatic conditions, reinforcing the need for periodic monitoring of the buildings to find potential damage. They propose two main approaches useful for the scanning of structures: photogrammetry and laser scanning. The first technology allows to obtain information about the state of a building through the analysis of captured images; this is usually accomplished using aerial devices and the accuracy is being optimized with the use of new artificial vision algorithms. On the other hand, laser scanning is faster in real time than photogrammetry; however, of the resolution is low, there is the risk of losing a high percentage of the data. Authors state that laser scanning can be used to detect cracks, presenting certain limitations when scanning at difficult angles and that recently, the terrestrial method is combined with aerial photogrammetry to achieve better results in scanning and generation of 3D models.

To carry out the experiment for this investigation, we used technological resources provided by the AdMaS Laboratory; however, due to the limits of this investigation, it was not possible to use drones to collect data. Although the AdMaS Laboratory had the necessary equipment available, certain legislative restrictions prohibit flying over the city center and residential areas (where field work was concentrated). Nevertheless, the possibility of carrying out a follow-up investigation in the future is not ruled out.

In this section, we will briefly introduce the analysed technological equipment and its characteristics in terms of its incorporation in the traditional method of the BRAIN network: a professional photographic camera, mobile scanner, and a static scanner, as well as a thermal imaging camera used in the current inspection method.

2.1. Professional photo camera

The camera provided by AdMaS was the Nikon D800 [3]. This is a professional digital SLR camera, with a "Full Frame" sensor of 36.3 megapixels produced by Nikon Corporation. To archive the images on the computer, a memory card adapter (PC Card Adapter EC-AD1) is necessary. This adapter allows you to insert Type I CompactFlash memory cards into PCMCIA card slots.

2.2. Mobile scanner

The device used for the collection of data from a moving vehicle was a mobile laser scanning system, model RIEGL VMX-450 [4]. This device allows extremely high measurement rates that facilitate the acquisition of data in dense point cloud format; the acquired data are characterized by being accurate even at high driving speeds; however lower speeds allow higher density of the points obtained. This will also depend on the configuration prior to the survey, where the distance between the points of the cloud is specified.

An additional 360° spherical camera, model FLIR LadyBug® 5 usb 3.1, with 30 megapixels resolution, was installed on top of the entire equipment stack. The image system covers 90% of a complete sphere. This works as a complement for applications in geographic information systems (GIS), vehicle-based photogrammetry and geographical reference information. In this procedure, the data collection is carried out *en masse*, generating a point cloud containing not only the facades of interest, but the entire urban canyon that the scanner can capture at 360°.

The software used to control and store the collected data was the POSPac MMS, a high precision program used for direct geo-referencing from mobile mapping sensors through the Global Navigation Satellite System (GNSS) and inertial technology. This software can be adapted for different data acquisition platforms, whether terrestrial, aerial or maritime. The subsequent data processing was done in the Riegl RiProcess software.

2.3. Static scanner

The static scanning device used was the FARO® Laser Scanner Focus 3D [5]. This is a high-speed three-dimensional laser scanner for detailed measurements and documentation. The device uses laser technology to produce extremely detailed three-dimensional images of complex environments and geometries in a few minutes. The resulting images consist of a set of millions of 3D measurement points. The scanner covers a field of vision of 360° x 305°. Point measurements are repeated up to 976,000 times per second creating a point cloud, a set of three-dimensional data, from the scanner's environment. Each of these scans has millions of scanned points, which can be predetermined according to the selected resolution which is determined by the points acquired per rotation. The result is a complete survey of the built environment visible in both black and white format and color format, facilitating reading when evaluating the intensity of perceived injuries. In this case, it is convenient to make use of the colored point cloud to facilitate the identification of smaller injuries.

Although the scan record is made on the basis of natural targets, such as planes, walls, corners, etc., the combination of additional artificial reference objects, such as spheres or chessboard paper targets, improves the results of the scanned environment and allow each object to be georeferenced. For the inspection using this equipment, per each facade the technician puts the scanner at a distance between 10 m and 15 m, allowing to capture a greater amount of the facade's point cloud.. Each inspection requires 25 to 30 minutes to process the data.

After the experiment, the data captured by the laser scanner are recorded on the removable SD memory card, which allows easy and secure transfer to SCENE, the FARO point cloud manipulation software.

2.4. Thermal imaging camera

The thermal imaging camera provided by AdMaS was the T420bx FLIR [6], which has a 320x240-pixel resolution screen that shows a preview of a thermographic image of the object on the lens. With the use of this technology, it is possible to early diagnose problems such as energy losses, thermal bridges, construction failures, water infiltrations, losses or failures of thermal insulators, etc.

The model used allows to measure an object's temperature ranging from -20°C to $+120^{\circ}\text{C}$ (-4°F to $+248^{\circ}\text{F}$) and from 0°C to $+350^{\circ}\text{C}$ ($+32^{\circ}\text{F}$ to $+662^{\circ}\text{F}$). The reference temperature can be set manually.

The software used to process the obtained thermographic images was the FLIR Tools, which offers a simple interface to import, filter and visualize images. Using the software, it was also possible to view location or orientation information stored by the camera's GPS.

3. Experiment and data collection design

In order to introduce new technologies to an existing inspection methodology, it was necessary to understand the environmental conditions required for the use of the equipment and to establish the inspection protocol on which the experiment was based.

3.1. Built environment sample under study

To carry out the inspection, an action protocol has been designed for gathering the environmental information on the city and the requirements of each device for its correct functioning during data collection.

In the case of scanners, fewer obstacles interrupting the scanning of the built environment improve the results. The sample selected for this experiment is located in Veveří and Jiráskova streets within the city district of Veveří. In the case of Veveří street, the traffic is higher, comprising private vehicles and public bus transport routes, as well as two tram lines for each traffic direction; this reduces the quality of the data collection. On the other hand, vehicle traffic on Jiráskova street is low because it is a secondary and one-way street, which enabled achieving a better imaging quality. These road conditions create inconsistent obstacles, which may result in varying quality of outcomes. However, both streets have trees on both sides of approximately 10 meters in height. This physical condition creates a permanent obstacle to data collection. It is for this reason that climatic conditions where the trees do not have leaves are required in order to limit the range of permanent obstacles.

Similarly, according to the Köppen climate classification, Brno has an oceanic limit climate (Cfb) and a humid continental climate (Dfb) with cold winters and hot summers. In the last 30 years the average temperature in Brno has ranged between 25.6°C on the hottest days of summer and under -4.3°C on the coldest days of winter, in mean terms [7]. To obtain more accurate data with the thermographic camera, it is recommended that the difference between the interior temperature of the building and the outside temperature is approximately 20°C . Therefore, the inspection was carried out when the outside temperature was much lower than the comfort temperature.

Due to the above reasons, the experiment was carried out in the autumn, specifically in October and November 2017, after the leaves had fallen off the trees and the minimum outside temperature reached -6°C .

3.2. Inspection methodology

The collection of data was based on the inspection using the LABEDI datasheet, created by the Building Laboratory in the Escola Politècnica Superior d'Edificació de Barcelona (EPSEB), covering the visual method in situ and the method using a professional photo camera.

The LABEDI datasheet includes two sheets: one designed to store the general data referring to the building and the second designed for the storage of particular data referring to the characteristics of each facade and the existing injuries to each facade facing the urban front.

The second sheet contains the types of injuries analyzed in the inspected built environment according to the following classification:

- Mechanical injuries caused by external or internal forces, having an effect on the mechanical integrity of construction elements: detachment, crack, debonding, spalling and deformation.
- Chemical injuries resulting from chemical reactions between the materials that make up the construction elements and atmospheric factors or other pollution contained in the surrounding environment: material degradation and corrosion.

- Physical injuries caused by the operation of laws of physics, affecting the physical characteristics of the construction elements and materials: moisture, as well as material degradation.

Each of these types of injuries is evaluated according to its extent by means of a visual inspection: punctual (P) when less than 25% of the element is damaged, local (L) when defects affect between 25% and 50% of the element, and general (G) when damage affects over 50% of the element. Injuries were also evaluated in terms of severity by assigning, for each of the elements, a numerical value ranging from 0 to 6 according to the severity of the damage observed in the element. This information allows to compute, numerically and graphically, the Weighted Severity Index (WSI) of the injuries as a weighted mean which allows the researcher to obtain a general picture of the global condition of the damage on the facade.

If \mathcal{E} denotes the set of existing elements in a facade, the WSI of the facade is determined by the weighted mean of the injury severities, across the elements in \mathcal{E} , with weights 1, 2 and 3 for the extent variable, that is

$$WSI = \frac{\sum_{i \in \mathcal{E}} (P_i + 2L_i + 3G_i)}{18 \cdot \text{card}(\mathcal{E})} \cdot 100, \quad (1)$$

where P_i , L_i and G_i denote the severities with punctual, local and general extent, respectively, being 18 ($=3 \cdot 6$), the potential maximum contribution of a defect, and $\text{card}(\mathcal{E})$ the cardinal of \mathcal{E} , i.e. the number of existing elements. The WSI represents the percentage of damage, in terms of severity and extent, of every facade and it is computed for the parts of the facade (body, deck railing, balconies and tribunes), as well as for each of the aforementioned injuries.

3.3. Data collection

The sample on which these inspections were carried out included five types of facades selected according to their morphology: (1) flat, (2) with balcony, (3) with tribune, (4) mixed, i.e. with balcony and tribune, and (5) a facade indifferent in morphology but with a remount (additional storeys added in the place of the original roof). For each facade, an inspection was made using each technological resource and the traditional method which includes the photo camera and the visual in situ inspection.

3.3.1. Professional photo camera. For the inspection with a camera, images were taken of each element that makes up the facade: baseboards, cornices, jambs and lintels, roof rails and any specific injury considered relevant for the previous assessment, as well as a general image of the facade. The resolution level of the camera and the number of images obtained allow an almost accurate assessment of the injury. However, the magnitude and intensity of the injury are not appreciated in the same way as in person. As seen in Figure 1, where the first row comprises the images obtained by the equipment and the second row contains an approximation of the area framed in the red square, almost all the peeling in the facade is seen in the lower zone, middle zone and upper zone, but, when calculating the WSI, a difference can be observed in comparison with the visual method in situ.

3.3.2. Mobile georeferenced scanner. The ease of collecting data provided by this equipment allows to survey the entire street in a matter of minutes. However, when carrying out the inspection, it is necessary to evaluate each facade independently by means of the associated point cloud. The amount of points collected, and the quality of the resulting color model, allows the assessment of large-scale injuries such as spalling. However, smaller defects such as cracks and deformations are not easily evaluated. In the case of the facade in Figure 1, the spalling damage can be seen, together with a detachment in the lower part of the facade (framed in red), but no more spalled elements can be seen due to the quality of the image derived from the point cloud.

3.3.3. Static georeferenced scanner. The software can provide color or black and white outputs. In this case, it is suitable to make use of the colored point cloud to facilitate the identification of injuries. The large number of points collected by the fixed scanner reflects a more detailed image that allows

perceiving smaller injuries. In Figure 1, we can highlight a greater number of chipping elements both in the lower area in which the largest injury is located, as well as in the middle and upper areas (each framed in red).

3.3.4. Thermographic camera. For a better result in the thermal image, the inspection was carried out when the outside temperature was at 3°C, between 6:00 a.m. and 8:00 a.m. when sunlight was not yet affecting the facades by increasing their surface temperature. It is apparent that at the time of the inspection, the quality of the image and the projected information did not complete the data in the best way. When focusing on the red frame in Figure 1, where the presence of the chipping injury is observed, no differences are distinguishable with respect to detachment damage. The injuries are not perceived as much as with the other equipment, but this device provides another type of information that is not taken into account in the LABEDI datasheet, such as heat leaks.



Figure 1. Image resulting from the survey with each evaluated technological resource provided by AdMaS, for the facade with remount.

4. Comparative analyses

Research carried out by authors such as Emelianov et al. [2], Pu and Vosselman [8], Clayton et al. [9], and Fernandez et al. [10] arrived at positive conclusions concerning the use of high-performance graphic capture technological equipment. Authors suggest that the extraction of lines from the facade with the use of images is quite precise, while laser points are better suited to obtain flat features, which is why the authors suggest using a combined system where the flat characteristics are obtained using laser data while the characteristics obtained through imaging are introduced later to refine the model.

From the data collected with each of the methods, the LABEDI datasheets were filled with the severity and extent values per element and injury, and WSI values were derived. Table 1 shows each of the WSI values for the detachment injuries on the five facades. Detachment defects are present in an estimated 17.09% of buildings in Brno [7].

For these values, a quantitative analysis with comparative graphs is performed to visualize the difference between data values according to the method used. As shown in Figure 2, a quantitative analysis of the detachment injury (Ds) on the mixed facade, the WSI with traditional visual method is 6.7, with photo camera 4.8, with the mobile scanner 1.3, with static scanner 1.3 and with the thermographic camera 0.0. Therefore, the results showed that, compared to the values obtained through visual inspection, the values that came closer were the ones obtained through using the Professional Photo Camera method, and the same applied in the case of the other facades. However, in the case of the thermographic camera, no values were recorded at the moment of inspection.

In order to perform a comparative qualitative analysis of the proposed alternative methods, we relied on the inspection methodology requirements applied in the BRAIN network [11]. For this, general and specific characteristics are analyzed. These requirements are based on a qualitative analysis table that allows recognizing the different characteristics of a particular methodology with an

overall weight for each specific requirement: identification (descriptive (6.34%), methodical (5.03%), universal (6.13%)), classification (sequential (5.89%), detailed (5.69%), ordered (4.67%)), methodology (robust (7.88%), standard (6.75%), quick (7.87%)), resources (technological (2.81%), human (3.94%), time (4.50%)), data quality (reliable (9.03%), quantifiable (6.64%), verifiable (5.58%)) and analytical skills (multifunctional (2.95%), processable (4.64%), longitudinal (3.66%)).

FACADE ID	TYPE	METHOD USED	WSI Ds
19166729-1	Remount	Traditional visual	9.5
		Professional photo camera	1.6
		Mobile georef. scanner	3.7
		Static georef. scanner	2.5
		Thermographic camera	0.0
30323584-1	Tribune	Traditional visual	6.6
		Professional photo camera	2.1
		Mobile georef. scanner	0.5
		Static georef. scanner	1.0
		Thermographic camera	0.0
19170505-1	Mixed	Traditional visual	6.7
		Professional photo camera	4.8
		Mobile georef. scanner	1.3
		Static georef. scanner	1.3
		Thermographic camera	0.0
19170912-1	Balcony	Traditional visual	17.7
		Professional photo camera	10.8
		Mobile georef. scanner	1.8
		Static georef. scanner	2.2
		Thermographic camera	0.0
19171200-1	Flat	Traditional visual	2.8
		Professional photo camera	1.4
		Mobile georef. scanner	1.1
		Static georef. scanner	1.2
		Thermographic camera	0.0

Table 1. Weighted Severity Index (WSI) for detachment injury values of each method on the five facades.

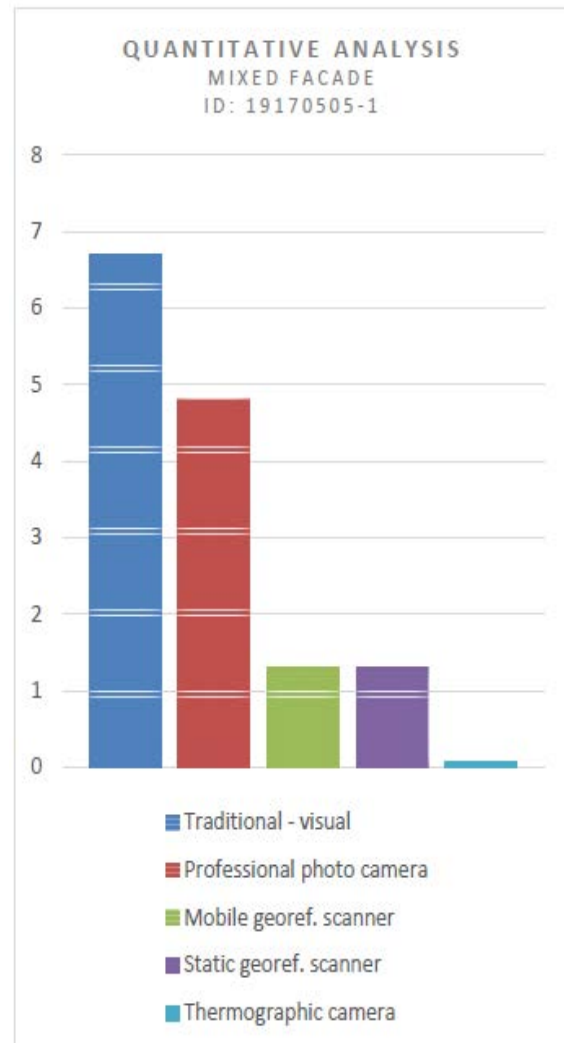






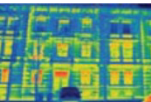
Figure 2. WSI for detachment injury values of each method on the mixed facade.

Table 2 shows the absolute and weighted scores obtained through the qualitative analysis, for the general and specific characteristics of inspection with the traditional methods used in the BRAIN network and the alternative methods presented in this paper. Each of the inspection methods applied has been classified with absolute values ranging from 1 to 5, shown in the left-side part of each column (score 1 for the worst and 5 for the best) allowing a preliminary general comparison among them, in absolute terms. Analogously, each score has been weighted according to the relative percentage of each specific requirement.

On the one hand, surprisingly, the traditional visual method had the highest overall score, with a 68 – 376.62, standing out among the other technological resources. On the other hand, from the beginning

a higher score was anticipated for the mobile georeferenced scanner, but the scores indicate that two others technologies showed similar or higher scores: the professional photographic camera and the static georeferenced scanner (60 – 328.57 and 59 – 321.36, respectively). In the case of the thermographic camera, scores showed the expect result, i.e. 32 – 175.55. Even though it shows an additional information that the other technologies did not, results do not allow to evaluate the most important information related to injury condition required according to the inspection datasheet.

Table 2. Qualitative Analysis for each method based on the Multiscale Predictive System of the Urban Front and the BRAIN environment requirements.

GENERAL CHARACTERISTICS		SPECIFIC CHARACTERISTICS		METHODS				
- FIELD -	- CRITERIA -	VISUAL	PROFESSIONAL	MOBILE	STATIC	THERMOIMAGE		
								
IDENTIFICATION	Descriptive	4.5 - 28.53	4.5 - 28.53	2.5 - 15.85	2.5 - 15.85	1 - 6.34		
	Methodical	4.5 - 22.64	4.5 - 22.64	2.5 - 12.58	2.5 - 12.58	1 - 5.03		
	Universal	5 - 30.65	4 - 24.52	1 - 6.13	2 - 12.26	3 - 18.39		
CLASSIFICATION	Sequential	5 - 29.45	3 - 17.67	3 - 17.67	3 - 17.67	1 - 5.89		
	Detailed	5 - 28.45	4 - 22.76	2 - 11.38	3 - 17.07	1 - 5.69		
	Ordered	3 - 14.01	3 - 14.01	3 - 14.01	3 - 14.01	3 - 14.01		
METHODOLOGY	Robust	5 - 39.40	3 - 23.64	3 - 23.64	3 - 23.64	1 - 7.88		
	Standard	3 - 20.25	3 - 20.25	1 - 6.75	3 - 20.25	5 - 33.75		
	Quick	4 - 31.48	3 - 23.61	5 - 39.35	1 - 7.87	2 - 15.74		
RESOURCES	Technological	5 - 14.05	4 - 11.24	1 - 2.81	2 - 5.62	3 - 8.43		
	Human	5 - 19.70	4 - 15.76	1 - 3.94	2 - 7.88	3 - 11.82		
	Time	3 - 13.50	5 - 22.50	2 - 9.00	4 - 18.00	1 - 4.50		
DATA QUALITY	Reliable	3 - 27.09	3 - 27.09	4 - 36.12	4 - 36.12	1 - 9.03		
	Quantifiable	3 - 19.92	2 - 13.28	4 - 26.56	5 - 33.20	1 - 6.64		
	Verifiable	1 - 5.58	3 - 16.74	4 - 22.32	5 - 27.90	2 - 11.16		
ANALYSIS	Multifunctional	3 - 8.85	2 - 5.90	5 - 14.75	4 - 11.80	1 - 2.95		
	Processable	3 - 13.92	2 - 9.28	4 - 18.56	5 - 23.20	1 - 4.64		
	Longitudinal	2.5 - 9.15	2.5 - 9.15	4.5 - 16.47	4.5 - 16.47	1 - 3.66		
Overall		68 - 376.62	60 - 328.57	53 - 297.89	59 - 321.39	32 - 175.55		

When carrying out these inspections, it is important to highlight the different positive and negative characteristics in the application of these resources for collaborative inspection that have been taken into account:

- The orthogonal images captured with the different equipment allows to see parts in depth that cannot be observed from the height of the inspector, e.g. surfaces just above the flight of the cornices.
- The quality of the obtained images, in the case of the photo camera, allows the inspector to magnify the image and see high definition details of the damage that the samples present. However, none of the resources allowed for easy evaluation of cracks. Other equipment made it almost impossible to distinguish injuries unless they were very serious, apart from information obtained during the previous traditional inspection.
- The average time required for data collection per facade using the alternative technological methods was lower compared to the traditional method; the overall comfort of the inspection

was also higher. One of the biggest obstacles are the trees and, in some cases, vehicles in front of the samples that obstruct visual observation in some areas; this makes it necessary to obtain additional data when such obstacles are present.

These initial conclusions are the result of field experience and the quantitative and qualitative assessments. For now, these analyses do not yield any conclusive results to rule out any of the evaluated resources or to replace the current method. Some capabilities of the technological resources have been demonstrated, proving their potential utility in data collection and the analysis stage of the inspection. It is important to emphasize that rather than an alternative ways of conducting an inspection, they are complementary tools for improving the quality and accuracy of the inspection.

5. Conclusion

The main objective of this research consisting in evaluating possible improvements to data collection and analysis using high-performance graphic capture devices provided by the AdMaS Laboratory at Brno University of Technology, in the framework of the collaboration with the EGAR research line, made it possible to establish strategies and opportunities during the process of inspection, and allowed to obtain greater knowledge of the scope of use of these pieces of equipment.

It is clear that the use of high-performance graphic capture devices reduces the inspection time per facade, facilitates the extraction of three-dimensional information, and provides dynamic data on the area. In this sense, although one could assume that the technological resources would allow better results at the moment of inspection with the LABEDI datasheet, the values of the different criteria were very variable in all the methods considered in this preliminary experiment.

Therefore, in order to obtain more robust conclusions, extensions of this experiment will be conducted in near future. Ongoing research has a greater scope regarding (a) the sample size, (b) the typology of facades, and (c) the combination of technological resources. Within this goal, which involves management of the LABEDI datasheet by digital means, we suggest to develop a digital interface that would automatically manage input data inserted, as well as to use different devices in combination in order to achieve better and more accurate results in the inspection and analysis processes.

Acknowledgments

To carry out the objectives of this paper within the framework of the Brno's Urban Laboratory, we collaborated with multiple entities. The authors wish to express their gratitude to Barcelona School of Building Construction (EPSEB), the Institute of Statistics and Mathematics Applied to the Building Construction (IEMAE) for the analysis of data, the Building Laboratory (LABEDI) regarding the methodology proposed in this study, the Brno University of Technology (BUT), in combination with the Advanced Materials, Structures and Technologies Laboratory (AdMaS), for providing the technological resources used in the study, and the City Council of Brno for supporting the gathering of information from the urban laboratory. This research has been partially supported by grants Nos. MTM2015-64465-C2-1-R (MINECO / FEDER) of the Ministerio de Economía y Competitividad (Spain) and 2017 SGR 622 from the Departament d'Economia i Coneixement de la Generalitat de Catalunya, and the SmartTransLog Erasmus+ Consorcium (2016-1-ES01-KA108-023465).

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