URBAN STRUCTURAL DAMAGE ASSESSMENT USING OBJECT-ORIENTED ANALYSIS AND SEMANTIC REASONING

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MARCH, 2014

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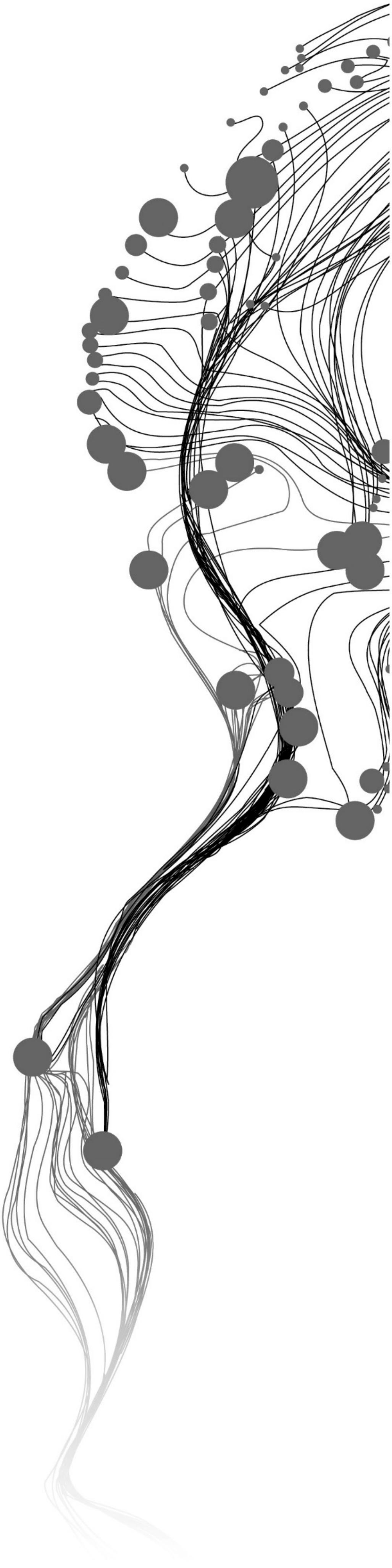

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Enschede, The Netherlands, APRIL, 2014

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
Specialization: Applied Earth Sciences: Natural Hazards and Disaster Risk Management

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ABSTRACT

Structural damage assessment is a priority following disaster events, but, especially in complex urban settings, remains a significant challenge. Many studies have explored the potential of remote sensing data, but in particular vertical data have been found to have substantial limits. Oblique imagery has been identified as a potentially more useful data source that provides multi-perspective information, overcoming the vertical view constrains of the VHR imagery. However, to date, damage mapping has just been based on individual (single perspective) images, and approaches at automated processing have been limited. This paper addresses damage assessment based on integrated multi-perspective oblique images obtained with an unmanned aerial vehicles (UAV). Object-oriented analysis (OOA) and 3D point-cloud assessment are used to extract damage indicators from both façades and roofs, including evidence of rubble, cracks and holes, as well as to identify damage in structurally critical locations, such as next to load-carrying beams. The research focuses on creating a methodology that tries to facilitate the always conflictive and ambiguous classification of the intermediate damage levels with the aim of achieving a more reliable per-building damage score. Acknowledging that damage assessment demands extensive expertise and experience we aim to provide a tool that automatically determines the comparatively clear damage cases (no/little damage and complete destruction), and for the intermediary cases creates an interface of the building in question with both the actual façade and roof images, with the option for an analysis to switch on additional damage layers to aid in the damage scoring. The results suggest that the developed OOA rulesets are capable of extracting the damage features, and are able to cope with different types of façades and architectural scenes. This study has demonstrated that the use of OOA to extract damage information from the buildings leads to a more comprehensive and less subjective building damage assessment. This results are specially interesting for stakeholders present at different stages of the disaster response, as well as for search and rescue teams and insurance companies.

ACKNOWLEDGEMENTS

Family, friends and Maria, thank you for helping me out to keep my mind calm, focus and happy to make this study possible.

I also would like to thank to my supervisors Norman and Markus for the guidelines and input they have given me along this period. Special thanks, as well, to all the people who collaborated with me and my colleague Mr. Kim in our filed visit to Italy and to all the experts that have helped giving some feedback in the study.

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1. INTRODUCTION

1.1. Background

Damage assessment is the evaluation of all the valuable things that have been adversely affected by the impact of a hazardous event. After a disaster, damage assessments are the main, and most of the times, the only, source of information that helps to understand the situation of the impacted area and its necessities. Hence, a rapid damage assessment is highly important because it provides vital information such as: area of impact, population at risk, estimation of the economic loss, structural stage of the buildings or guidelines for the search and rescue (SAR) teams (Barrington et al., 2011). The building, or structural damage assessment (SDA) is the branch of the damage assessment whose aim is to evaluate the state of the buildings after a given event It is a priority following disaster events and, especially in complex urban settings, remains a significant challenge.

1.1.1. Ground-based VS. Remote sensing-based structural damage assessment

There are two main ways to proceed with a SDA: by ground-based surveys that, with organizations such as the Building Assessment Team (Stanford-University, 2013) or the Earthquake Engineering Field Investigation Team (EEFI, 2013), make on-the-field SDA; or by remote sensing-based techniques that, with institutions such as United Nations Institute for Training and Research (UNITAR, 2013) or the Cambridge Architectural Research Limited (CAR, 2013), use image analysis techniques to evaluate the damage after a given event (Kerle & Hoffman, 2013).

Ground-based surveys provide a very detailed assessment and, in case of collaboration of large numbers of trained volunteers (Kerle, 2010), they can cover large areas within a few weeks. However, this approach is slow and it has terrain related difficulties to cover the affected areas (Gerke & Kerle, 2011a). Although alternative and faster approaches for ground-based mapping are being tested, for instance, the use video cameras mounted on cars (Curtis & Fagan, 2013), for the rapid assessment purposes, remote sensing techniques still fit better the requirements. Even though remote sensing based approaches are more uncertain and tend to underestimate the damage in comparison with the ground surveys. (Lemoine et al., 2013).

It is worth to mention that the SDA, no matter the chosen approach, has to deal with the uncertainty and the subjectivity of the damage' complex nature (Corbane et al., 2011). The damage is expressed in a different way depending on the structural type of the building (Okada & Takai, 2000) or the soil on where it was built (Ince, 2011), among others. These factors will add even more complexity to this task.

1.1.2. The evolution of the remote sensing for structural damage assessment

The first remote sensing photograph was taken in 1858 and, already in 1906, George Laurence was obtaining images of the damage produced by the earthquake in San Francisco (Figure 1) using a system of kites (Baumann, 2001).

Figure 1. George Laurence's photo of the San Francisco after the earthquake in 1906.

Remote sensing was identified as a useful tool for damage assessment from its very beginning. Since then, the entire range of platforms has been used with many different purposes, within the damage assessment scope: digital aerial images to detect damage caused by earthquakes (Yamazaki et al., 2008) or the use of very high resolution (VHR) and satellite images to extract parameters of the vulnerability of the building in Europe (Mueller et al., 2006), are two examples of different platforms used for damage assessment. In Kerle et al (2008) more examples can be found.

While some scientists were exploring the capabilities of the available platforms, at the same time, some of them were also investigating the possibilities of the different types of data. Ehrlich et al. (2009), Dell'Acqua et al. (2011) and Khoshelham et al. (2013) studied, optical, radar and LIDAR for damage assessment purposes, respectively. These are the most popular data types, but there are other approaches that use different data types, for instance, thermal data (Rodarmel et al., 2002). For a deeper review of the data and the platforms used for damage assessment see Kerle et al. (2008) or Dell'Acqua & Gamba (2012).

The data, the platform and their combination define the spatial dimension where the damage is going to be assessed. A study dimension can range from 2D to 4D (Figure 2). The majority of the studies have been done using single, mono-perspective, vertical, optical, 2D imagery. For instance, Li et al. (2010) studied an approach where damaged areas are identified in 2D images and Barrington et al. (2011) described a crowdsourcing approach to do a SDA based on the same kind of imagery. However, these 2D-based studies, although straightforward and popular, assume a serious simplification of the reality. They assume that the expressed damage in one of building's captured perspective is representative, and can be extrapolated, as the damage for the whole building. On the field it is not rare to see buildings where only one façade or the roof is collapsed and the rest is still standing and without any visible damage. In such a case, the SDA of a single façade or roof would lead to a wrong result; besides, the uncertainty which is assumed on the final result by taking into account only one of the multiple possible scenarios. Studies are taking place to try to integrate the information from the different viewing angles of the buildings, for instance, Gerke (2011), who worked on a supervised classification of multiview objects for earthquake SDA, but a proper understanding of how to integrate and summarize this information is still missing.

Moving towards a higher dimensional understanding of the building, there are studies, such as Elberink et al. (2011) or Khoshelham et al. (2013), which assess the affected buildings in the 3D space. In both cases, the damage assessment is done on the point cloud, a data type that has been recognized as a very well suited for SDA due to its capabilities to capture the geometry of the buildings (Shen et al., 2010). These studies seem to be able to easily identify those features that classify a building as intact or collapsed due to their geometric understanding of the scenario.

Damage can be also studied in 4D, 3D plus the temporal dimension. As seen in Tong et al. (2012), they used pre- and post-disaster satellite stereo imagery to detect damaged buildings and Schweier et al. (2004) used a very complex approach with CAD models and damage simulations. Although these studies have highly accurate results, the pre-disaster information is not available for many parts of the world (Corbane et al., 2011), so a SDA based on this data is not always possible.

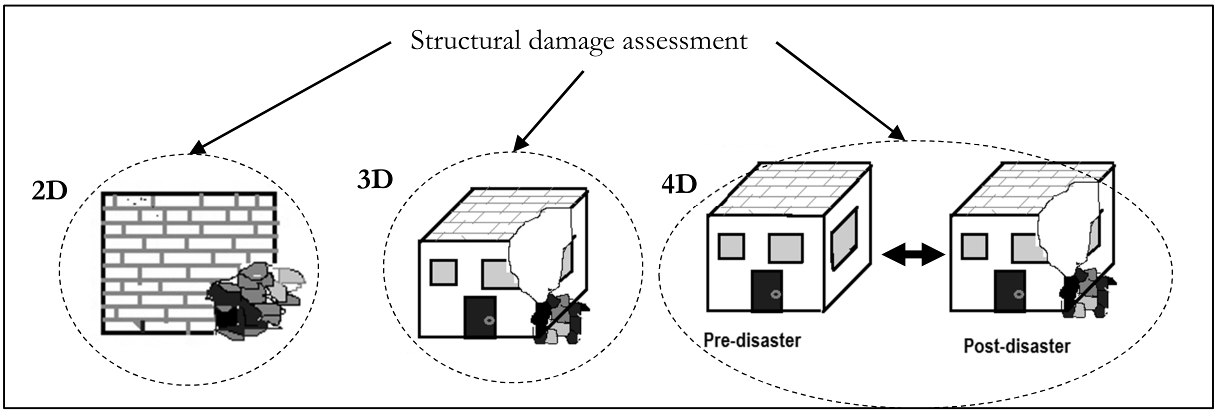


Figure 2. Illustration of the three different dimensions where the damage can be studied. From left to right: a classic vertical view of the roof of a building, the post-disaster 3D model and two 3D models pre- and post-disaster situation.

1.1.3. Limitations of the conventional remote sensing approach

For both, spaceborne and airborne sensors, and for any kind of data, the spatial resolution has increased up to the cm range. It has been increasing up to a level where the pixels have lost their importance, and the objects of interest on the images are now made up of clusters of pixels (Blaschke, 2010). But, despite this increase in the resolution, the amount of damage information extracted from the images has reached a limit, and it is not related to the spatial resolution (Gerke & Kerle, 2011a). This limitation has to do, mainly, with the viewing angle of the sensors, besides other limitations of the image-based analysis per se. Most of the conventional platforms only take images from a vertical (close to nadir) perspective, which facilitates the correlation and georeferencing, but only provides information from the roof of the buildings. This limitation has been already noticed by Gerke & Kerle (2011a), and it stands as a strong limitation for a complete SDA because of the fact that for reaching a full understanding of a given building, its façades and roof have to be visible in order to produce reliable damage scores.

The drawbacks of this vertical perspective have been tried to solve by using non-conventional oblique imagery. The standard oblique images are characteristic because of being taken from approx. 45° with the ground, which affects to their integration with other datasets (Kerle et al., 2008) and adds problems related with occlusion that also increases the uncertainty of the final damage score. However, at the same time they provide more reliable information from the façades which is highly important for a proper SDA. Examples of this approach are Mitomi et at. (2001) using oblique images from TV footage in order to identify damaged buildings, or Rasika et al. (2006) doing multi-scale texture and colour image segmentation for damage detection.

A more sophisticated and systematic approach within the oblique imagery is offered by Pictometry Inc. (2013). Pictometry Inc. generates images from 5 viewing directions and location information that facilitates the integration of the images (Pictometry, 2013).The use of Pictometry imagery for SDA (Gerke & Kerle, 2011a; Xiao et al., 2012) has been demonstrated as an interesting approach for more complete and comprehensive damage assessment of individual buildings (Corbane et al., 2011). Saito et al. (2010) have evaluated the correspondence between some remote sensing approaches (space- and air-borne) and the

ground-based surveys done after Haiti's earthquake in 2010. They showed that the damage mapping done using Pictometry imagery was more reliable than any other remote sensing approach, although it still had problems with the occlusion and underestimation, as any other remote sensing approach (CAR, 2010). The more conflictive results, when using Pictometry, were found when the damage of the building was intermediate, that is when the damage is mainly represented on the façades and its description in the EMS-98 is too vague. Besides these limitations: occlusion, underestimation and vague damage descriptors, the SDA by oblique imagery is still limited due to the expert's finite ability to identify the damage in an image (Kerle & Hoffman, 2013) but it was highlighted as the most reliable dataset to carry out the damage mapping (CAR, 2013).
With the new perspective given by Pictometry imagery, the term "comprehensive" starts to be present. Gerke & Kerle (2011a) already included this term, which is related to the fact that with the multi-view imagery, a more holistic assessment of the façades and roofs of the building is possible. Although the term "comprehensive" was included in their study (Gerke & Kerle, 2011a), and other studies, like Gerke (2011), that address the integration of multiview data, there is still a lack of a fully comprehensive assessment where information from different perspectives, occlusions and conflicting data is integrated in a proper decision making tools that helps to create more realistic per-building damage assessment. An interface where that multi-perspective building environment is enhanced and allowed to proceed with the assessment of the damage is still missing.
After the Haiti earthquake the amount of remote sensing data released had no precedents, optical, SAR, LIDAR (Corbane et al., 2011). Pictometry data were also available for the three big organizations World Bank (WB), UNOSAT and the Join Research Center (JRC) on charge to produce the first damage map of the area (Corbane et al., 2011). However this kind of collaborative scenario does not happen that frequently and Pictometry data is rather expensive. For this reason alternative ways to obtain oblique imagery had to be found and looking towards a handier and cheaper production of this imagery, everything point out to the Unmanned Aerial Vehicles (UAV).
The use of UAVs, such as the one made by Aibotix (2013), the Aibotix X6 (Figure 3), seem to be a good combination of operability and image quality. Besides, it produces both, oblique and vertical imagery, which permit the production of point cloud data (Harwin & Lucieer, 2012). And, as it was said before, point clouds capture very accurately the geometry of the buildings which, in combination in the optical images, build up a robust dataset for SDA that allow a complete understanding of the building.

Figure 3. Aibotix X6 UAV (Aibotix, 2013)

The use of UAVs for SDA, at the neighbourhood level, seems to bridge the gap between the classic remote sensing techniques and the ground surveys and it has been showed as an excellent solution for data acquisition on disaster situation (Nonami et al., 2010). It can be said that the UAVs combine the image acquisition of the remote sensing with the flexibility of the ground-based approaches.

1.1.4. Image analysis techniques for structural damage assessment

Remote sensing for structural damage assessment is based on the image analysis to identify and evaluate the damage indicator in order to assign a damage level that represents the building state. There are three main streams in image analysis for SDA: visual interpretation, pixel-based image analysis and object-oriented analysis (OOA). Visual interpretation is based on the analyst capacities to manually identify damage indicators and it has been used widely within the International Charter Space and Major Disasters

(International-Charter, 2013) and other institutions such as the Cambridge Architectural Research Ltd. (CAR, 2013). Pixel-based image analysis is based on a semi-automatic classification that uses the information stored in the pixels. And object-oriented analysis (OOA), on the other hand, is a semi-automatic technique that creates objects from the clusters of image pixels, where a combination of image processing and GIS skills is done in order to combine the spectral and the contextual information (Blaschke, 2010).
Visual analysis approaches still need the voluntarily work of large number of trained people in order to be time efficient; besides, the subjectivity of the damage assessment and the personal differences of the experts affect to the results of this analysis (Kerle & Hoffman, 2013).
Pixel-based and object-based image analysis have been tested for semi-automatic post-disaster image analysis in Yamazaki et al. (2007). In that study, it was shown that the OOA approach provided more accurate results than the pixel-based one; however, it is something that depends on the complexity of the environment and on the skills of the analyst. Anyway, object-oriented analysis technology, being a knowledge driven approach and a technology that tries to simulate the human cognitive process, makes easier to bring the knowledge about the damaged buildings into a semi-automatic SDA. It stands as the most appropriate image analysis technique to deal with the complex information that the UAV imagery presents about the façades and roofs.

1.1.5. Structural damage scales

There is no unique and standard damage scale for structural damage assessment; there are many types of damage scales. The scales could be classified according to their aim: safety or damage classification. These two terms are related and they use the same damage indicators to proceed with the classification, which many times leads to confusion. For the safety assessment, in documents such as the ATC-20, a field manual for post-earthquake safety evaluation of buildings (ATC, 2005), or the AeDES, another field manual for post-earthquake damage and safety assessment and short term countermeasures (Baggio et al., 2007), the absence of damage indicators in a building implies the higher level of safety. On the other hand, for the damage evaluation, in documents such as European Macroseismic Scale of 1998 (EMS-98) (Protezione-Civile, 1998), the absence of damage indicators implies the lowest damage level.
Due to its wide use in the post-earthquake community (Corbane et al., 2011), the EMS-98 is the most used scale, for both, the ground-based surveys and the remote sensing damage mapping, although it was made for in-the-field surveys where all the building's perspectives are in principle available. The EMS-98 compromises 5 damage levels (Figure 4), from D1: slightly damaged, to D5: complete destruction. Being a scale made for ground surveys, its mayor constrain is that it describes the damage for the façades more in detail than the damage for the roofs, which has been a problem for the damage assessments based on vertical imagery (Gerke & Kerle, 2011a). Furthermore, the EMS-98 was made to classify entire buildings and not to address the part of the building visible from the remote sensing sensor's point of view.

Besides the mentioned limitations, this scale seems to have for the remote sensing approach, its description of the intermediate damage levels tends to be too general and focused in wall's indicators. This issue has led to notable classification conflicts in the intermediate damage levels when different remote sensing techniques are compared. It has been proved that the remote sensing techniques going from VHR satellite data, vertical airborne data and Pictometry tend to underestimate the damage due to the conflicts in the intermediate damage levels (CAR, 2010).

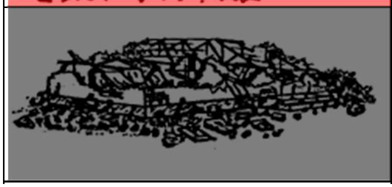
	**Grade 1: Negligible to slight damage (no structural damage, slight non-structural damage)** Hair-line cracks in very few walls. Fall of small pieces of plaster only. Fall of loose stones from upper parts of buildings in very few cases.
	**Grade 2: Moderate damage (slight structural damage, moderate non-structural damage)** Cracks in many walls. Fall of fairly large pieces of plaster. Partial collapse of chimneys.
	**Grade 3: Substantial to heavy damage (moderate structural damage, heavy non-structural damage)** Large and extensive cracks in most walls. Roof tiles detach. Chimneys fracture at the roof line; failure of individual non-structural elements (partitions, gable walls).
	**Grade 4: Very heavy damage (heavy structural damage, very heavy non-structural damage)** Serious failure of walls; partial structural failure of roofs and floors.
	**Grade 5: Destruction (very heavy structural damage)** Total or near total collapse.

Figure 4. The 5 different levels that are assumed in the European Macroseismic Scale 1998 (EMS-98) (1998). Grade 1 = D1, Grade 2 = D2, Grade 3 = D3, Grade 4 = D4 and Grade 5 = D5

1.2. Problem statement

With the purpose of creating a new methodology capable of dealing with the post-disaster multiview imagery to generate more comprehensive damage scores by presenting the extracted damage information to the experts, and then aggregating this information to the building level, this proposed study has to deal with the following main problems:

a) Understand the complex environment of the damage assessment.

Starting from the raw, overlapping, oblique imagery of a UAV, and ending up in a per-building damage score. The first challenge is to create an efficient and robust methodology that integrates the different processes and products to generate damage scores and accomplishes the requirements of the several stakeholders active in this domain.

b) Identification and extraction of the damage information using OOA.

The rich level of detail of this type of imagery requires a proper definition of the relevant damage indicators that have to be extracted. Then, the development of rulesets: the segmentation and classification processes, based on a OOA's dedicated software (Trimble-eCognition, 2013), that is capable to deal with such a complex set of images, remains as a core task. OOA has been used on this field before, but never at such a level of detail. It implies that the entire approach of the ruleset development, and specially the segmentation stage, remains as a challenge.

c) Visualization of the extracted features.

The information extracted by the OOA rulesets has to be presented to the expert analysts who are going to proceed with the per-view (per-façade/roof) structural damage assessment. The interface where the multi-perspective information is presented is a very important element that has to help to generate more reliable damage scores and has to create the environment where that comprehensive SDA understanding is clear.

d) Implementation of the EMS-98.

The damage scale EMS-98 is a scale made for on-the-field surveys where all the perspective of the building are available and are taken into account to classify the entire building within the range of the EMS-98 damage levels. However, in this study, the EMS-98 has to be re-interpreted in order to fit the per-façade/roof requirements of this study, besides of including a certainty measurement to try to evaluate the performance of the experts when dealing with the use of the EMS-98 outside its preferred scope.

e) Construction of the algorithms that integrate the multi-view SDA into the per-building level.

When the per-view damage score and its certainty measurement have been created by the expert, a tool to aggregate that information into a per-building damage score is required because the final outcome of this study is a per-building damage score and a certainty measurement. These two aggregation tools are meant to recreate the understanding of the on-the-field surveyors who, walking around the building, come out with a per-building damage score. However, this process is done on-the-field by the experts and there are no standards about how it must be done.

1.3. Research objectives

The general objective of the proposed study is to create a methodology that, by making use of the UAV imagery, is capable to address the SDA in a more comprehensive way that allows to produce more reliable per-building damage scores. This objective is divided in several sub-objectives:

1. Create a methodology that covers the entire scope of the proposed study.
2. Demonstrate the use of 3D point-cloud data as a reliable dataset to identify the higher damage levels of the EMS-98.
3. Identify the damage features that have to be extracted from the images
4. Find the best approach to segment the images highlighting the damage features.
5. Develop a set of rulesets capable of working with different images and provide semantic meaning to the extracted features.
6. Design a scenario where an expert could proceed with the per-view SDA and that includes a certainty measurement.
7. Create two algorithms where the per-view damage assessment results and the certainty measurement are integrated into a per-building score.
8. Analyze the performance of the decision tree by creating an environment where a real situation could be tested
9. Test the usability of the interface where the experts will analyze the images.

1.4. Research questions

1. How to organize the information flow?
2. What are the products that have to be produced from the raw UAV imagery?
3. What are the main damage features that should be extracted by OOA?
4. How to segment the images in order to highlight the damage features?
5. What must be the aim of the OOA rulesets: accurate feature extraction or to highlight the damage features in the image?
6. How to create an OOA ruleset that works in more than one scenario?

7. Which is the best way to present the extracted damage information to the experts?
8. How to integrate the per-view SDA score and the certainty of the classification into a single per-building score?
9. How to add a measurement of the uncertainty in the final damage score?
10. How to test the usability of the interface?
11. How the performance of the two aggregation algorithms can be tested?

1.5. Research approach

The study, due to data constraints, was carried out in a way that allowed to work in different tasks independently from each other and, at the same time, it was planned in perspective to be able to make a logical history out of it. Figure 5 illustrates the approach followed

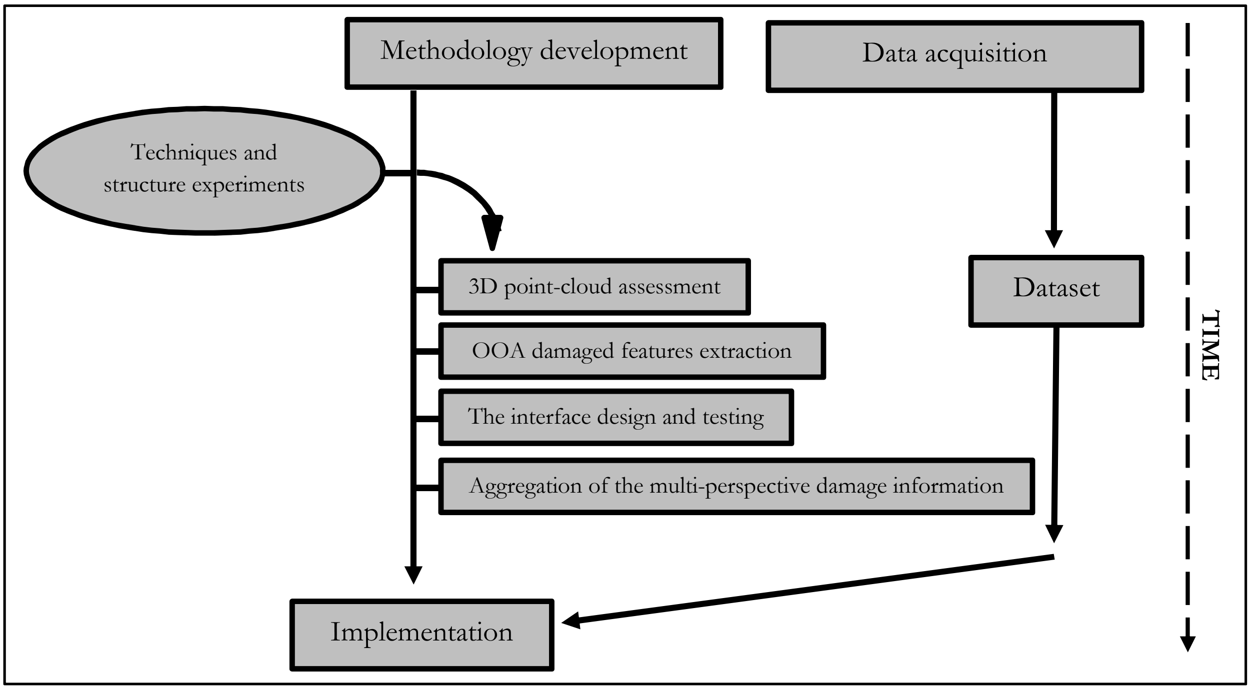


Figure 5. Illustration of the approach followed to accomplish the objectives proposed in this study.

Chapter 1: Introduction. A description on what has been done on this field is done, from the general to the specific. The problems are pointed out, the gaps are identified and the objectives to be addressed are specified.
Chapter 2: Literature review. A more detailed description of the different approaches on this field are explained. The different approaches are categorized according to the data, platforms, and image analysis techniques used.
Chapter 3: Methodology. The designed approach to accomplish the proposed objectives is described in this chapter. Each step of the methodology is described as: purpose, dataset, software, methodology and expected outcome.
Chapter 4: Results. The outcomes of the processes described in the methodology are presented in this chapter where they are put in context.
Chapter 5: Discussion. The results are discussed according to whether their purpose was accomplish or not and noting all the deficiencies found in their application
Chapter 5: Conclusion and recommendation. A brief conclusion of the whole study and the answers to the proposed research question are presented. In the recommendation section the lines for future research are pointed out.

2. LITERATURE REVIEW

The reasons that support why this study had to be done now are presented in the previous chapter. In this chapter a deeper description of the different approaches that have been tried, the reasoning behind them, an explanation of where they have failed and to what have they derived, are addressed. This chapter is sorted by the used platforms following a top-down approach. Within each section, the most used data types, the dimensions where the damage was assessed and the image analysis techniques used are addressed accordingly.

2.1. From the cameras on kites to the cm resolution

Setting this first milestone in the use of remote sensing for damage assessment, after George Lawrence and his camera mounted on a kite, the amount of improvements and achievements on this field has been overwhelming. Nowadays with companies such as Skybox (2013), which offers sub-meter imagery and even meter resolution video footage, the remote sensing possibilities have taken a leap. However, as it was said in the previous chapter, not everything has to do with the spatial resolution; there are many other factors that have an effect on the quality of the structural damage assessment.

2.1.1. Spaceborne sensors

Starting with the sensors that operate at the highest altitude, the satellites; their use for damage assessment have suffered tremendous changes. The high resolution (HR) sensors, with coarser spatial resolution than 10 meters, have been used for damage assessment. Examples are Chen et al. (2005), who used the SPOT 5 (2002 - date) in order to assess the areas affected by the December 2004 Indian Ocean's Tsunami or Morton et al. (2011), who used the Landsat (1997-2004) and the MODIS (2000-2005) to map the canopy damaged by the forest fires in the Amazon. In both cases the areas evaluated are large, in the order of 3 thousand hectares, and the techniques used to analyse the images were pixel-based. The size of the pixels in this kind of imagery, 10 m or bigger, does not fit the requirements for a per-building structural damage assessment. According to Dong and Shan (2013), in order to classify the damage of a building in several damage levels, the resolution of the sensor has to be increased up to the meter or the sub-meter level. For these reason, approaches based on this HR imagery, cannot be called building damage assessment studies, they are damage assessments.

At the beginning of the 21st century, three very high resolution (VHR) satellites were launched: IKONOS (1999) GEOEYE (2000) and Quickbird (2001), setting the new standard. All these satellites' imagery, and more that have come, such as Skybox (2013), with around 1 meter resolution or finer, were suitable for per-building damage assessment, according to Dong & Shan (2013). It was at this stage when the object-based image analysis technique starts to stand as an alternative to the pixel-based techniques for damage assessment; the pixel had lost its importance (Blaschke, 2010).

In this VHR imagery, a single object such as a roof, is made out of a cluster of pixels, and its essence is better captured by an object-based image analysis technique (Yamazaki & Matsuoka, 2007) rather than for a pixel-based technique. There are many examples of the use VHR satellite images and OOA for damage assessment. For instance Tiede et al. (2011) who used pre- and post-event VHR satellite imagery in combination with OOA to extract the shadows of the buildings and then derive rapid damage maps; or Li et al. (2010), who detected building damage using an OOA approach and a one class support vector machine

technique. Although the complexity and the level of detail of the images suggest the use of object-based techniques, there are also studies done on the pixel basis. Pasaresi et al. (2007), using a pixel-based approach, assessed damage on built-up areas affected by tsunamis; it is worth to mention that they pointed out that an object-based analysis must be carried out in the future because better results could be achieved.
OOA stands as a semi-automatic image analysis technique that is capable to deal with more complex and detailed imagery due to its two steps approach: segmentation and classification. However, it still has to cope with some level of subjectivity, mainly related with the selection of the parameters for first segmentation step where the pixels are grouped in objects. Although some studies, such as Drăguţ et al. (2010) are working on methods to create an automatic determination of the thresholds used in that step, still, in many cases, the trial an error approach is the most efficient.

Although these studies based on VHR imagery, according to Dong & Shan (2013) started to reach the level of building damage assessment, with their sub-meter spatial resolution, still, they do not allow a classification of the damage level. The outcomes of these mentioned studies used to be just binary per-building classifications: collapsed or standing building. Besides, the VHR satellite imagery, as it was mentioned in the previous chapter, it is constrained by its close-to-nadir viewing angle that only provides information from the roofs of the buildings which also limits the differentiation of the different damage levels.
It's important to mention that, with the level of detail that this imagery allows, a main damage assessment technique is still the visual interpretation. Many organizations, such as the International Charter (International-Charter, 2013) or the Cambridge Architectural Research Ltd. (CAR, 2013), base their assessments in this technique. Visual interpretation of VHR satellite data reaches high levels of accuracy (Corbane et al., 2011), but they require large amounts of experts to process the vast sets of images, although there is a tendency to use the crowdsourcing power (Kerle, 2010), and it is still biased by the analysts' expertise and judgments (Kerle & Hoffman, 2013).
Within the spaceborne sensors, apart from the optical data, the use of Radar must be mentioned. With the launch of radar satellites, such as the TerraSAR-X, the production of VHR radar images, which are independent of the cloud cover situation, can be released within days after the event (Dell'Acqua & Gamba, 2012) and have been used for building damage assessment. Examples of the use of radar for building damage assessment are: Ehrlich et al. (2009) who used VHR radar data to identify damaged buildings and Shao el al. (2009) who used multi-source SAR data for damage assessment after the Wenchuan earthquake. Although the use of radar data leads to accurate identification of damaged buildings, up to date, the detailed SDA providing different levels of damage is still not possible (Dell'Acqua & Gamba, 2012).

2.1.2. Airborne sensors

There is a huge amount of data that comes from the airborne sensors, mainly optical and LIDAR data. The analysis of VHR airborne optical data has been widely used for SDA. For instance, the GEO-CAN consortium (ImageCat, 2011) used VHR aerial photographs in order to identify and tag the building damages after the Haiti earthquake in 2010 and Yamazaki et al. (2008) used aerial photographs to identify damaged buildings and then compared two semi-automatic image classification techniques: pixel- and object-based techniques. In these studies, the use of such a detailed imagery, in combination with the visual analysis (ImageCat, 2011) and the semi-automatic pixel or object-based analysis (Yamazaki et al., 2008) allow to exploit the textural characteristics of the buildings to derive the different damage levels. Indeed, it has been showed that the use of airborne imagery for SDA obtains better and more accurate results than the approaches that use spaceborne imagery (CAR, 2010).
The other mainstream airborne sensor, which has been found as very useful for structural damage assessment, is the LIDAR. Shen et al. (2010) highlighted the use of point clouds for this purpose because

of its ability to capture the geometry of the buildings. Studies such as Khoshelham et al. (2013) who used 3D point segmentation to classify damaged buildings' roofs, or Elberink et al. (2011) who used a similar approach to detect collapsed building by segmenting the point clouds, are top illustrations of this technique. These two examples represent the potential of such an approach which, among the immense complexity of a damaged area, can reach accurate results and identify collapsed houses, roofs or rubble piles. However, LIDAR data it is made to capture geometrical information, not to capture texture information, although the new sensors include a basic RGB sensors; this implies that a complete SDA cannot be possible. It is not possible because in many cases the damage features, such as cracks, are only visible with textural information and they cannot be captured in LIDAR data.

As it was mentioned before, spaceborne and airborne imagery, regardless the kind of data: optical, Radar or LIDAR, all the mentioned approaches have a common limitation which is not related to the spatial resolution (Gerke & Kerle, 2011a), it is related to the viewing angle. Despite the increase in the resolution, down to the cm, the expert analysts, by visual interpretation, by pixel-based or object-based techniques, cannot extract more information than the related to the damage suffered in the roof and its surroundings. Most of the conventional platforms only allow the production of vertical imagery, which regarding to the EMS-98, does not facilitate a complete SDA because for it, information of the façades is also required. For this reason, the approaches that make use of vertical data are limited to produce aggregated damage classifications. In these studies the extremes are easily identified: intact and collapsed, but the intermediates are summarized in one class (Ogawa & Yamazaki, 2000), and that it is a simplification of the reality caused by the constraint imagery.

2.2. From vertical to oblique imagery.

As it was pointed out above, the vertical imagery does not allow a complete building assessment because a relevant part of the information is missing: the façades. This issue was tried to overcome by using non-conventional imagery, the oblique imagery. In the introduction chapter this type of data were described as a kind of imagery that is taken from approx. 45° off the ground. This viewing angle, despite the fact that the images are more difficult to integrate (Kerle et al., 2008) and might have occlusion problems which difficult the image analysis (CAR, 2013) and increase the uncertainty of the damage score, provides more reliable information for the SDA (Mitomi et al., 2001) concerning to the façades and roofs of the buildings.

2.2.1. First attempts with oblique imagery

The first approaches that exploited oblique imagery made use of TV video footage. Mitomi el al. (2001) tested aerial video footage to map the damage after the earthquakes and Rasika et al. (2006) used it to proceed with a multi-scale and texture colour segmentation for damage classification. The low cost of this imagery and the rapidness of its production after an earthquake were the main drivers for its use. However, although there were studies, such as Weindorf et al. (1999), to overcome the problems of the low quality, this still remains as a challenge for this approach.

In this same line of the oblique imagery, Altan et al. (2001) experimented with transverse images of CCD cameras and Geographic Information Systems (GIS) in order to proceed with the SDA of buildings and their structural elements after an earthquake. Although the results are very accurate, the detailed information needed does not fit with the rapid damage assessment requirements after an earthquake (Gerke & Kerle, 2011a).

2.2.2. Pictometry

The method to take oblique images has been improved and more systematic and efficient capture techniques were developed, one of the most popular is Pictometry (2013). Pictometry imagery consists on sets of 5

images with different viewing angles: 1 standard close to nadir image and 4 images looking towards the four cardinal direction: North, South, East and West, besides the location information which is used to facilitate the integration (Pictometry, 2013).
The advance of the oblique imagery with regards to the conventional vertical imagery is that the façades are visible now. Studies such as the one carried out by Xiao, Gerke and Vosselman (2012) clearly demonstrate the usability of this data, without any extra information, for façade analysis. Then, studies which use either visual analysis or object-based techniques, more focused on the actual SDA, empathize the quality and detail of the information obtained from Pictometry for the per-building damage assessment. The report done for the ImageCAT inc. by the CAR (2013) compares the visual analysis of the Pictometry imagery with the on-the-ground SDA and the VHR satellite imagery-based SDA done by GEO-CAN. This report showed how the use of Pictometry reached higher accuracies detecting and classifying damaged buildings than the studies based on VHR satellite imagery. Other studies based on more automatic techniques like OOA, such as Gerke & Kerle (2011a), defined Pictometry imagery as a well suited data for comprehensive semi-automatic damage mapping. However, an implied drawback in Pictometry imagery studies is still the occlusion. This issue increases the uncertainty of the provided damage score and it has been pointed out as one of the reasons why the Pictometry data, although its accuracy and correctness is better than the reached with more conventional imagery (Lemoine et al., 2013), still underestimates the damage in comparison with the ground truth (Lemoine et al., 2013).
Besides the information that can be extracted directly from the pictometry data, oblique imagery in general, can be the source to produce very detailed and dense point-clouds, which stand as a very appropriate dataset to capture the geometry of the buildings (Shen et al., 2010). Some studies have experimented already with this dataset, although produced from LIDAR instead of by image matching. For instance, Khoshelham et al. (2013) classified the damage of a building in relation to the state of the roofs and Elberink et al. (2011) experimented with the use of point-clouds to identify collapsed buildings. Again, LIDAR results as a very well suited data to capture the geometry of the buildings, but for a complete SDA, it must combined with detailed imagery, otherwise, part of the information is missed because it cannot be captured.

2.2.3. The future of close range oblique data

Nowadays, the technology has allowed to have very robust and stable UAVs, for instance, the hexacopter made by the German company Aibotix (2013) (Figure 3). UAVs have been showed as an excellent solution to work in disaster situations (Nonami et al., 2010) and some studies, such as Wen et al. (2012), have tested their application in disaster situations. Although, so far, there is not much literature about the use of UAV's oblique imagery for structural damage assessment, it is known that they provide high quality and very detailed images that cover the façades and roofs of the target buildings from all their viewing angles. Besides, very dense point-clouds of these buildings can be derived using the same techniques as the studies focused on Pictometry imagery carried out (Gerke & Kerle, 2011a, 2011b). The use of UAV imagery opens a huge range of option that, due to the image detail and flight flexibility, seems to be able to bridge the gap in between the remote sensing and the ground-based approaches.

Through this literature review the evolution of the techniques used for damage assessment and more in detail, for structural damage assessment have been presented. The conclusion is that the use of oblique optical imagery as a data source to generate point-clouds and detailed images of roofs and façades which, due to their complexity, will be analysed with object-oriented analysis techniques, stands as a new alternative to generate more comprehensive per-building damage scores that take into account all the faces of a building.

3. METHODOLOGY

The methodology can be divided in 4 different stages: **3D point-cloud assessment**, **OOA damaged features extraction**, **interface design and testing** and **aggregation of the multi-perspective damage information**. These four stages were designed and then tested on a set of images obtained from real case scenarios.

This methodology set up was already an outcome of this study, since one of the objectives was to develop an approach to cope with the entire scope of the study. Figure 5 below illustrates the structure of the methodology created in order to accomplish with the study's goals.

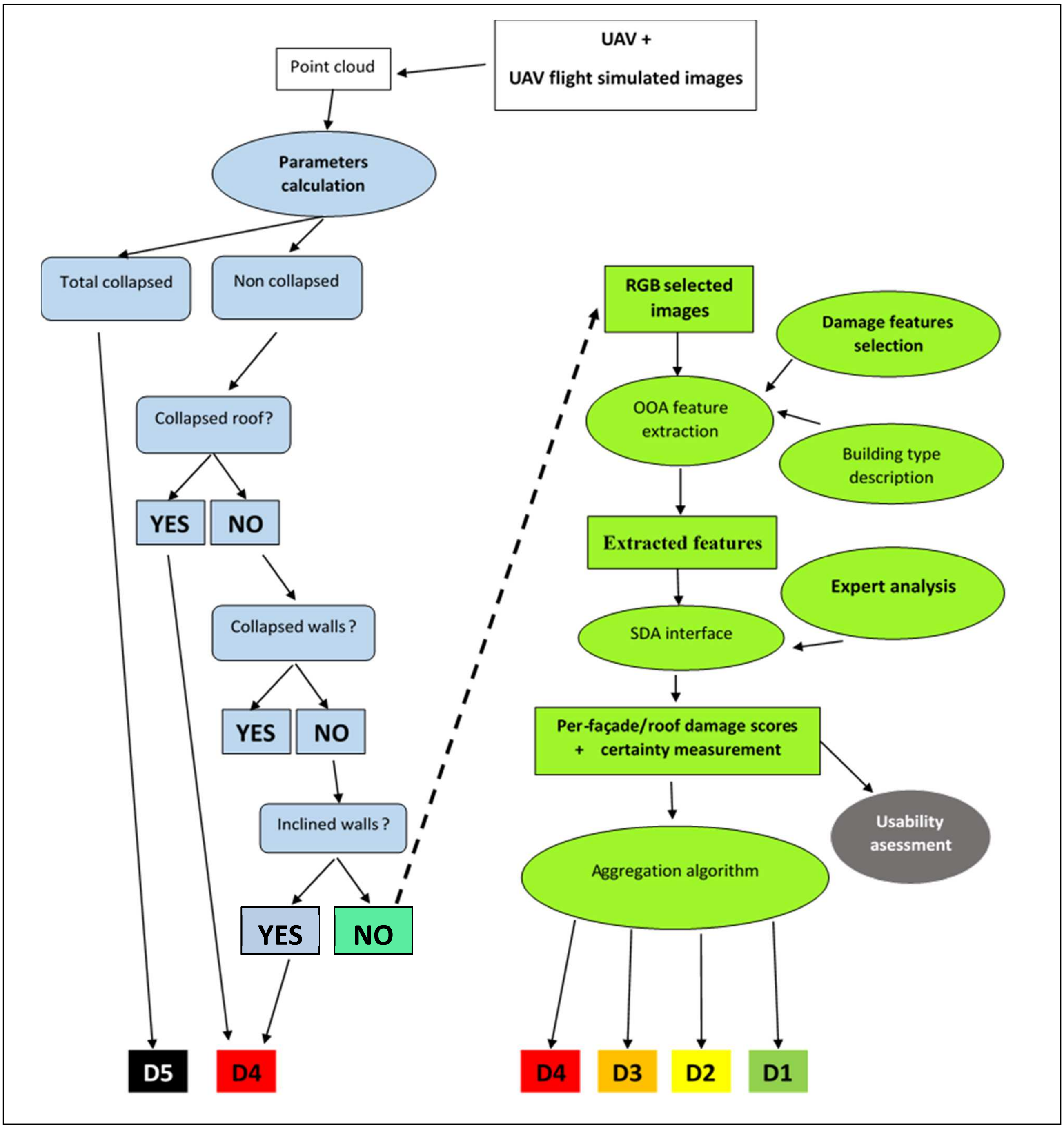


Figure 6. Flowchart describing the methodology of the study

The flow through the methodology (Figure 6) is: the UAV would be fly around a certain location, and the images would be processed to produce a 3D point-cloud. The point-cloud would go through a number of processes where evidences of D5 or D4 damage are searched. First, the building would have to pass the test where the indicators for total collapse are sought. If it was not collapsed, the standing parts would be evaluated. Starting from the roof, if it was not collapsed the next step would look for rubble pile on the sides of the building and if there were not rubble piles, the last step would check for possible inclination of the façades. If none of this evidences were found, the building would be considered as a standing construction with roof and standing non-inclined walls suitable for the next step of the methodology. It is worth to mention that after this 3D point-cloud assessment, the building could still be classified as D4 if one or more of its walls would have fallen towards the inside without creating any rubble pile in the outside. The selected images that capture the façades and the roof the building would be processed in OOA, which would look for the previously selected damage features. These features would be presented to the SDA experts in the interface, interface that creates the environment where the different perspectives of the building are taken into account. The expert would classify each façade or roof within the EMS-98 and this per-façade/roof information would be aggregated into a per-building level which would be the final result of the methodology, a more reliable and comprehensive per-building damage score.

The different stages of these methodology are going to be explained on the basis of: purpose, dataset, software, methodology and expected outputs. But first, an explanation of how these data waere gathered and managed throughout this study is done.

3.1. Data management.

The data were obtained at two different locations: one in Italy, during the field visit done there, and another one in Gronau, Germany, at the demolition of an old factory.

Italy

Most of the images used in this study were taken in the northern part of Italy, in the surrounded villages at the North of Bolognia. The area, which was affected by a strong earthquake a few years ago, had a large number of standing buildings that still presented the effects of the shaking in their façades and roofs.

Gronau

Another set of images were taken in Gronau; an old factory was going to be demolished and we were allowed to fly the UAV .

As it was said, part of the images from Gronau were taken with the UAV, however, in northern Bolognia and the rest of the images taken in Gronau were taken with a camera attached to a 8 m pole that simulated the perspective of the UAV (Figure 7). A careful planning was carried out in order to simulate the UAV flight and to obtain oblique overlapping images of the scenarios.

Figure 7. Left: photo of the UAV ready to be launched in Gronau. Right: the MSc candidate Mr. Kim simulating the perspective of the UAV in Italy

The complexity of the developed methodology and the constraints found to obtain images of damaged façades and roofs, forced to this study to use different groups of images to test the several proposed hypothesis. In the table below (Table 1) a relation between the different datasets used throughout the thesis is presented. The relation in between the names and the images could be found in the appendix: Table 15 & Table 16.

3D point-clouds assessment	
Detection of completely collapsed building	Italian building 3
Detection of collapsed roofs	Gronau's factory
Detection of rubble pile in the surrounding of the building	Italian building 2
Detection of inclined walls.	Italian building 4
OOA damaged features extraction	
Roofs	Roof 1 & 2
Concrete façades	Concrete façade 1, 2, 3, 4, concrete façade 1,2 & 4 edited.
Brick façades	Brick façade 1,2 & 3
Interface design and testing	
Initial 3D model	Italian building 1
2D-based SDA	Concrete façade 1, 2, 3, concrete façade 2 edited
3D-based SDA	Inclined wall 3D model + Brick façade 1 & 2.

Table 1. Inventory of the data used in the different stages of the methodology.

3.2. 3D point-clouds assessment

3.2.1. Purpose

The aim of this very first step was to show, by visual inspection, that the identification of buildings that presented features that would classified them as D5 or D4 buildings (**total collapse**, **collapsed roof**, **rubble piles** and **inclined walls**) was possible by the analysis of their 3D point-clouds. At this level, the entire building was assessed so the damage score derived was already at a per-building level. Besides this objective, the 3D point-cloud assessment process also granted that the images of façades and roofs that reached the next part of the methodology, the OOA damaged feature extraction, were part of building with all their structural elements still standing.

3.2.2. Dataset

Overlapping images were the data source for this part of the methodology. Sets of overlapping images that captured the structure of 3 buildings in Italy and one building in Gronau (Table 1) were the starting point to derive the point clouds that were indeed used to support this method. The images were first processed to calculate the relative position of the camera and to create the local coordinate system (LCS) and then, they were processed in specific software for dense matching to finally generate the 3D point-clouds of the buildings (Figure 9 & Figure 8).

Figure 9. Point cloud of the "Italian house 2"

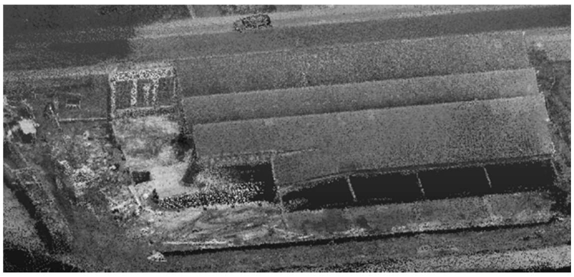


Figure 8. Point cloud of the "Gronau's factory"

3.2.3. Software

123DCatch (2013) was the software used in order to calculate the LCS and the relative positions of the camera; and SURE (2013), a software solution for multi-view stereo, was the software that enabled the derivation of dense point clouds from a given set of images and their orientations. These two packages were used to produce the final 3D point-clouds.

3.2.4. Methodology

The methodology followed to obtain the evidences that supported that it was possible to identify the already mentioned features to classify an entire building as D4 or D5 could be divided in:

- **Image acquisition**. The UAV or the camera attached to the pole were used to create the dataset with the overlapping RGB images.
- **Point-cloud processing.** First, 123D-Catch (2013) was used to create the LCS and then, using the dense matching software SURE (2013), a point cloud of the building was created.
- **Calculation of the z-component in the point-cloud**. The z-component represents the absolute value of the cosine of the angle enclosed by the vertical axis of the LCS and the normal vector of a plane fitted to the local neighborhood (e.g. the 10 closest points) of the respective point. The z-component would take a value of 0 when the plane is vertically oriented, i.e. its normal is horizontal, and it would be 1 if the plane is horizontally oriented, i.e. the normal is vertical. In other words, points on vertical walls would have a z-component value of around 0, while for points on flat roofs it would be 1.
- **Segmentation.** The segmentation of the point-cloud based on the z-component. Note that not all the buildings needed to reach the segmentation step, only the buildings where the rubble piles wanted to be identified.

Except for the image acquisition (UAV control not included) and the first part of the point-cloud processing, the rest of the data preparation was carried out by Dr. Markus Gerke. The visual interpretation of the outcome of the data preparation was, again, fully accomplish independently of any external help.

3.2.5. Expected output

The expected output was a set of four buildings where the visualization of the z-component, or its segmentation, demonstrated the presence of the indicator: total collapse, collapsed roof, rubble piles or inclined walls, which could classified the entire building as D4 or D5. This information would be the one provided to the SAR in order to help them to identify the areas where they should focus their activities.

3.3. OOA damaged feature extraction

3.3.1. Purpose

The aim of this step in the methodology was to develop a set of rulesets capable to find, classify, extract and give a meaning to the damage features that were found reliable to carry out a proper structural damage assessment in each face of the building. These rulesets, that are an ordered numbers of commands that apply different algorithms which segment, identify and classify the objects of an image (Fadel, 2013), had to be specific enough to extract the required features and, at the same time, they had to be able to mine those same damage features in different scenarios. For this reason, the definition of the rules that extracted the geometrically and spectrally different features, had to lie on overlapping characteristics that, regardless of the scenario, were present in all the images.

3.3.2. Dataset

For the OOA damaged feature extraction, 12 different images (Table 1) represented the test dataset where the rulesets were going to be applied. From this 12 captions, 2 of them represented roofs, 7 were concrete façades and 3 were brick façades examples. As it was said before, since the analysis was done in a per-view basis, the images were processed independently, they were not addressed as being part of a specific building. Due to the complexity of the images, before these images were processed (Figure 10), the areas of interest were selected, getting rid of parts of the image that were not reliable for the SDA, such as, the surrounding ground or the sky. However, although it would have been possible, to include extra rules in the rulesets would have added more complexity to the already complicated environment of analysis.

Figure 10. Example of how the images were edited in order to focus the analysis in the main part of the façade

3.3.3. Software

The OOA damaged feature extraction was carried out using eCognition Developer 8.8. a software tool developed by Trimble (2012) which stands as one of the most popular software packages on the field; between 50-55% of the papers published in OOA make use of this software package (Blaschke, 2010).
ArcGIS (ESRI, 2013) was used to digitized the real damaged feature directly from the original images. This software provided enough tools to create an appropriate reference dataset.

3.3.4. Methodology

The first step was to identify the damage features that could be extracted from the images and that could provide enough information to the experts to proceed with their assessment. In order to do this, an extensive literature review was carried out. The reviewed documents were: the ATC-20 (Field manual: Post-earthquake safety evaluation of buildings) (2005), the EMS-98 (European Macroseismic Scale) (1998) and the AeDES (Field Manual for post-earthquake damage and safety assessment and short term countermeasures) (2007).
Once the target damage features were listed, an OOA process, which relies on the ruleset, had to be designed. The OOA rulesets can be divided in the following way:

- **Segmentation**. The step where the pixels of the image are clustered in groups regarding to the algorithm's parameters that the user had defined. In this study, the segmentation process was done using a sequence of two algorithms: i) a multi-resolution segmentation and ii) a spectral difference segmentation algorithm. The determination of the required thresholds for the segmentation algorithms was done by carrying out a number of experiments where the effects of the different values were observed.

- **The feature analysis**. The characteristics of the objects were studied in order to identify the reliable features that were going to help in the classification. These features had different nature: spectral, geometrical or contextual. The finally selected features must fulfill an extra condition, they had to remain significant for the classification in the different scenarios because the rules were based on them

- **The classification.** With the reliable features identified, the classification step was meant to generate a set of rules that gave the desired meaning to the identified objects. In the classification process there were, as well, refining processes meant to exclude objects that were wrongly classified.

- **The export.** The classified objects were exported in a vector format to ArcGIS in order to manipulate them in a more appropriate environment.

For this study 3 different rulesets were developed in order to cope with the different building parts and building types: the roof, the concrete façade and the brick façade rulesets.

After the OOA extraction process, every image went through an accuracy assessment. The accuracy assessment (Joshi, 2010) was based on a set of statistical measurement that compared the areas (Joshi, 2010) of the extracted damage features and the area of the previously digitized damage features in ArcGIS (ESRI, 2013). Comparing these two datasets three indicators were derived: False Positive (FP), False Negative (FN) and True Positive (TP) (Figure 11). A set of accuracy measurements (Figure 12) were derived out of those three indicators.

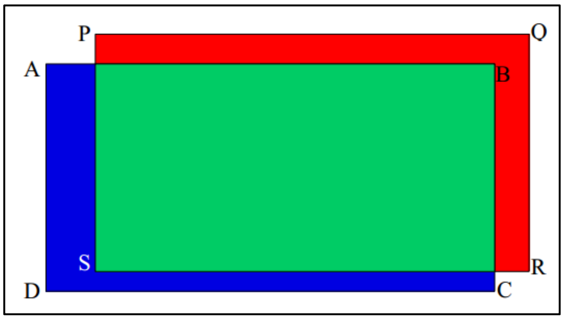


Figure 11. Illustration of how the accuracy assessment was proceed: green = TP, Blue = FP and Red FN (Joshi, 2010)

$$\textit{Split factor} = \frac{TP}{FP}$$

$$\textit{Missing factor} = \frac{FN}{TP}$$

$$\textit{Correctness} = \frac{TP}{TP + FP}$$

$$\textit{Completeness} = \frac{TP}{TP + FN}$$

Figure 12. Illustration of the 4 accuracy measurements calculated for the accuracy assessment (Joshi, 2010)

Besides the accuracy assessment, an experiment was performed with the aim of showing the effect of how the number of rules affected to the amount of information extracted and to the stability of the ruleset. Due to this, the image "concrete façade 3" was selected and 10 extra rules were added in the concrete façade ruleset, in order to over fit it to the mentioned image. The amount of extracted information by the over fitted ruleset was compared with the balanced ruleset. The hyperfitted ruleset was also compared when it was applied to other images in order to test its stability. A parallel comparison of the hyperfitted ruleset and the balanced one was carried out.

3.3.5. Expected output

The expected output from this step of the methodology, which could be considered the core of the thesis, could be differentiated in 4 groups: a list with the target damage features that had to be extracted, a shapefile per image containing the vector files of the classified objects, a set of statistical accuracy measurements per image and an illustration of the effect of the number of rules in the amount of extracted information and the stability of the rulesets.

3.4. Interface design and testing

3.4.1. Purpose

The aim of the interface was to present the information extracted from the images to the experts that were going to carry out the actual SD. The objective was to reduce the conflicts in the classification when the

damage fell within the intermediate levels (D1-D3), according to the EMS-98 (1998). The interface was also meant to integrate the multi-view information which, up to now, it had not been integrated in any environment. Besides, the interface provided the platform to include a measurement of the certainty of the classification.
Two approaches to visualize the information were proposed in the same interface: i) an approach that relied, mainly on the 2D images and ii) another approach that relied exclusively on a 3D environment. The interface was created for the first approach, where the experts could proceed with a complete experience on the interface. Due to data constraints, the second approach was only presented in the interface as an example that could lead to further research.

3.4.2. Dataset

For the first approach a 3D model and a set of 2D processed images (Table 1) were used to illustrate the interface. For the second visualization approach, the extracted damage features from two images from Italy and the 3D model of the same building were used (Table 1)

3.4.3. Software

The ESRI software: ArcGIS 10.1 (2013) was used to overlay the exported vector objects from eCognition over the original images. The interface was developed exclusively using Microsoft PowerPoint and 123D Catch (2013) was used to generate the two used 3D models.

3.4.4. Methodology

The two approaches to present the extracted information were integrated in the same interface. The methodology to create the interface could be summarized in the following steps:

- Interface design and PowerPoint implementation.
- Simulation of a real case scenario.
- Questionnaire design.

Two approaches to present the damage information were presented in the same interface, although only the one based on the 2D images was going to be fully implemented. A description of the followed steps to create these visualizations is explained below.

SDA based in a 2D environment.

- Creation of the 3D model of the building using image matching techniques (Autodesk-123D, 2013)
- Overlaying the extracted information over the original images by using a GIS software (ESRI, 2013).

SDA based in a 3D environment.

- The 3D model was created using the same image matching techniques (Autodesk-123D, 2013)
- The original images were exchanged with the classified images which contained the damage information.
- The damage information was visualized in the same 3D environment provided by Autodesk-123D (2013)

The final step of this part of the methodology was to find and send the interface to several SDA experts that were going to provide with their SDA expertise by trying to solve the presented real case situation.

3.4.5. Expected output

Part of the expected output was an interface where the information extracted by OOA could be presented to the experts in the better way possible. The other expected output was a real set of per-façade/roof damage scores that included a certainty measurement of the classification. Furthermore, the SDA experts were asked to give feedback and comments on the interface which represented the last expected outcome from this section of the methodology.

3.5. Aggregation of the multi-perspective damage information

3.5.1. Purpose

The purpose of the last step of the methodology was to develop two decision trees (aggregation algorithms) able to comprehensively aggregate the damage scores and the certainty measurements which were coming from the different viewing angles and that had to be aggregated at the building level. These decision trees were meant to reduce the ambiguity of the SDA by taking into account all the faces of a building.

3.5.2. Dataset

There were two different datasets: i) a real set of per-façade/roof damage scores which came from the experts' assessment of the exercise presented in the interface, and ii) a sample of randomly generated sets of 5 damage scores created artificially in order to test the performance of the decision tree.
Both datasets were made out of groups of 5 per-façade/roof damage scores, from 0 to 4 (D0 - D4) regarding to the used scale EMS-98 (1998) and each damage score included a certainty measurement that the expert assigned to his/her classification.

3.5.3. Software

R studio (2012), an open source project for statistical computing, was used in order to create an environment where the aggregation of the information and the implementation of the decision trees as an algorithms was possible. It was also used to generate random sets of damage scores and certainty values that simulated the expert's outcome in the interface.

3.5.4. Methodology

This stage of the methodology was divided in three parts: **simulation of expert SDA per-façade/roof scores**, **implementation of the decision trees in R** and the **algorithms testing**.

- **Simulation of expert SDA per-façade/roof scores**. R was used in order to generate a table filled with the simulated SDA expert's outcome (damage scores and certainty measurements).
- **Development and implementation of the algorithm.** Two decision trees that aggregated the damage and certainty scores had to be developed and had to be translated into an algorithm that worked within the R studio's environment (Figure 13).
- **Algorithms test.** The simulated expert's outcome and the real expert's outcome were ran through the implemented decision trees in order to evaluate their outcome and to extract the conclusions of their performance.

Extent of the damage	Building EMS-98 score
One view = D4	D4
> 50 % view = D3	D3
< 50 % view = D3	D2
> 50 % view = D2	D2
< 50 % view = D2	D1

→ R algorithm

Figure 13. Illustration of how the theoretically described algorithm has to be translated into R.

3.5.5. Expected output

The expected outcome at this final step of the methodology was: i) two algorithms that aggregated the information from the per-façade/roof level to the prebuilding level and ii) two sets of aggregated per-building damage scores and certainty measurements; one set which came from the aggregation of the real expert's outcome and another set which came from the aggregation of the simulated expert's outcome.

This methodology section has tried to explain the approach followed to accomplish the listed research objectives. The 3D point-cloud assessment with its visual interpretation of D4 –D5 evidences. The OOA damaged features extraction and its definition of reliable damage features and the entire, from scratch, ruleset development. The interface design and testing to create an environment where to enhance the multi-perspective damage assessment. And finally the aggregation of the multi-perspective damage information to summarized the per-façade/rood damage tags into a single per-building indicator.

4. RESULTS

In this chapter, the results of the previously described methodology are presented. The same structure as in the methodology chapter is followed, first, the **3D point-cloud assessment** part is explained, followed by the **OOA damaged feature extraction** and then **the interface design and testing** and it finalizes with **the aggregation of the multi-perspective damage information**.

4.1. 3D Point-cloud assessment

As it was mentioned before, this part of the methodology was meant to visually identify the buildings that presented D4 or D5 damage evidences and to ensure that the images that were going to be the input for the OOA damaged features extraction, were standing, not inclined façades and roofs. In this chapter the evidences found that supported the proposed methodology are going to be presented. The structure of this section is going to follow the same top-down structure as in the flowchart presented in the first chapter (Figure 6).

4.1.1. Collapsed – non-collapsed classification

The first step of the process had to do with the differentiation between the collapsed and the still standing buildings. This differentiation was very important since the collapsed buildings could be classified directly as D5, the highest score in the EMS-98. A D5 implied complete destruction of the building, and hence, a potential spot for the SAR teams to focus their search and rescue activities.

In this case, the value of the point-cloud's z component, which was already explained in the methodology section, was used to find the evidence of complete collapse. In Figure 14 it can be seen how, when the directions of the local neighbourhood's normal changed randomly indicating parts of the building that were having a messed up structure, the value of the z-component was a good indicator to prove it. In Figure 14 the colours from green to blue to purple illustrated those structural problems.

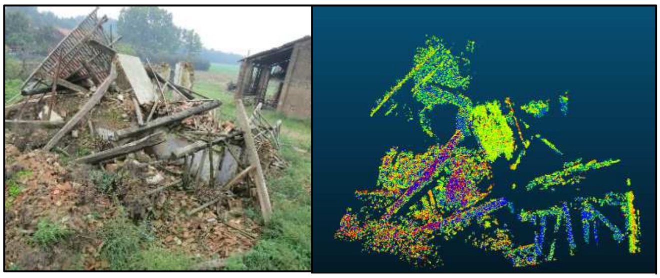


Figure 14. Visualization of the calculated z-component in the "Italian house 3". The different colours represent the different values from 0 to 1 of the z-component.

In the other hand, the visualization of the same parameter in another building's point-cloud (Figure 15), where the structure was still standing, the z-component clearly illustrated that the façades were standing. The values of the z-component, now, were more uniform and sharper, indicating that they corresponded with a standing building (Khoshelham et al., 2013).

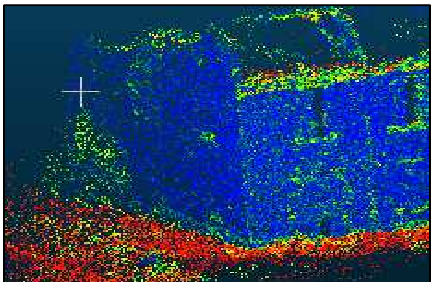


Figure 15. Visualization of the z-component in the "italian house 2". Blues colours representing horizontal elements, red colours for the horizontal parts.

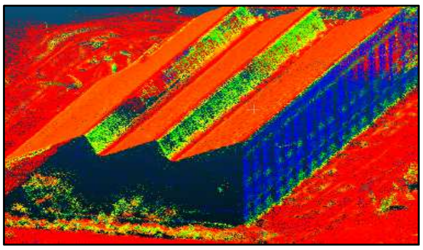


Figure 16. Visualization of the z-component in the “Gronau’s factory”. In blue the horizontal elements, in orange the more horizontal ones

4.1.2. Standing – collapsed roof

The second step had to be focused on one of the most important elements of the buildings, the roofs. The roofs were perfectly identified by the z-component’s value; in Figure 16 it can be seen how in blue, the façades are very well differentiated from the roofs, that in this case, were orange-red.

In Figure 17 an intact roof could be discriminated from a collapsed or an affected roof by making use of that same z-component value. An intact roof had a smooth red-orange color which indacated that all the points had a similar orientation, however, the affected roof showed a colour transition that indicated that the roof had collapsed. A point-cloud segmentation based on this parameter could clearly differenciate big homogeneous intact segments from the smaller changing affected parts like the one presented in Figure 17 (left) (Khoshelham et al., 2013)

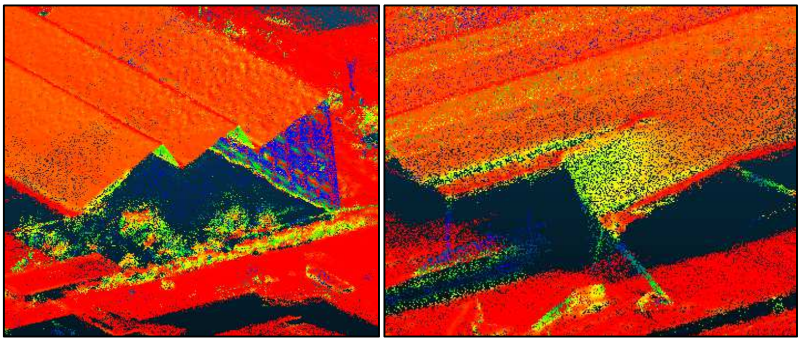


Figure 17. Comparison of two parts of the roof, one intact that kept the homogeneous colour and an affected part where the colours shift from orange to yellow indicating a change in the orientation.

A building with a collapsed roof, when the walls are still standing, would be the example of a D4 building, where, one again, the SAR teams would have to focus their activities to look for trapped people.

4.1.3. Rubble pile detection in the building surrounding

With the surrounding of the building also easy to identify due to their horizontal orientation, it was also straightforward to identify the presence of rubble piles which would be an indicator that, although the roof and the majority of the walls would be still standing, some parts of the façade might have been severely affected by the shaking.

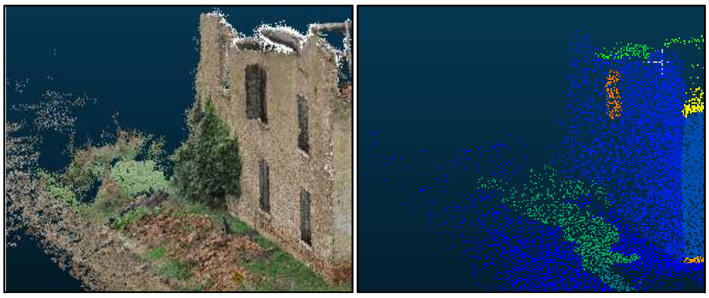


Figure 18. Visualization of the z-component in the “italian house 2”. The rubble pile in green was identified due to its different orientation regarding to its surrounding.

As can be seen in Figure 18, in this case, proceeding with a point-cloud segmentation based on the z-component, the presence of a rubble pile in the surrounding of the building can be easily captured. The green artefact in front of the façade was representing the mentioned rubble piles The presence of such a rubble pile would be an indicator of a D4 building that had suffered severe structural damage.

4.1.4. Façade's basic geometry assessment

This last step was meant to identify those façades that had suffered heavy structural damage and did not show evidences of rubble piles in their surroundings. In such a case, many façades tend to be severely inclined. Visualizing the z-component in the point cloud, an inclined wall could be easily differentiated from a non-inclined wall. In Figure 19, the same wall, but with the façade's point-cloud manually inclined, it could be observed how clear this inclination would appear in the point cloud. In Figure 19, the z component is almost 0 (blue) for the vertical wall, meanwhile, for the inclined wall, the z component is about 0.3 (green). An inclined wall in this case would be an indicator that would make the entire building to be classified as a D4

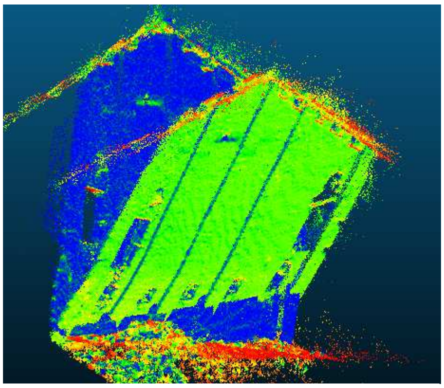


Figure 19. Visualization of the effect of the inclination of a wall in a façade with a simulated inclination. Blue colour for the horizontal and green colours for the inclined parts.

As it has been demonstrated in this section, the use of 3D point-clouds, and specially, with the visualization of the z-component, could show the indicators to classify the buildings that would have suffered heavy structural damage (D4) or that would had been completely destroyed (D5); besides of filtering the buildings that would had been less severely affected and that would need a more detailed image based analysis to be classified within the EMS-98 standards.

4.2. OOA damaged features extraction

In the coming subsections the selected damage features and the description of the OOA rulesets for the three different scenarios (roofs, concrete façades and brick façades) are explained.

4.2.1. Damage features selection

After the literature review of documents such as the ATC-20 (2005), the EMS-98 (1998), the AeDES (2007), the meetings that took place in Italy and the emails exchanges with David Lallemant, expert on the field of the structural damage assessment, the damage features found reliable for this SDA approach were:

Features that could be found in the façades (Figure 20):

- **Cracks**
- **Holes**
- **Interaction of cracks with structural elements**

Features that could be found in the roofs (Figure 20):

- **Moved tiles**

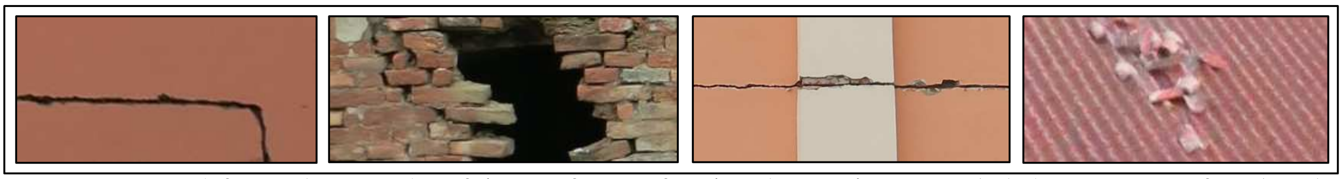


Figure 20. From left to right, examples of damage features found in the test dataset: crack, hole, interaction of crack with structural element and moved tiles.

The presented damage features were the focus of the rulesets developed in the coming step. For the identification and classification of those features, several other non-damage features had to be classified as well: façade, windows and columns.

4.2.2. OOA extraction rulesets

All the developed OOA rulesets for the extraction of the damage features were based on the same strategy. The damage features were elements presented in façades and the roofs that did not fit with the general pattern presented in them and that tended to be very well differentiated from their background. Hence, the segmentation part of the ruleset had to be able to aggregate the homogeneous objects and highlight the objects that did not fit with their environment and used to be related with the damage features. If this was achieved in the segmentation, the only focus of the classification part of the ruleset was to use the given objects characteristics, specially: area, maximum difference, relative border to -, asymmetry, rectangular fit and compactness, to give to the objects the meaning they had in reality.

4.2.2.1. Roofs

All the roof images (Table 1) were analysed with the same ruleset. This ruleset's aim was to identify the **moved tiles** feature, being the simplest of the three. It was designed to highlight and then classify the features that did not match with the main pattern of the image, in this case the roof tiles. The full details of this ruleset are presented in the appendix (7.4).
The ruleset consisted in two steps:

1. **Segmentation**. It was done in two steps that combined two segmentation algorithms that were part of eCognition (2013). i) The multiresolution segmentation algorithm, a bottom-up algorithm that locally minimizes the average heterogeneity by consecutively merging pixels that fit both: the spectral and shape homogeneity parameters (Trimble, 2011) and ii) a spectral difference segmentation algorithm whose purpose was to merge neighboring image objects according to their mean image layer intensity values. The neighboring image objects were merged if the difference between their layers mean intensities was below the value given by the maximum spectral difference. The selected parameters for the given algorithms were (Table 2):

Algorithm	Parameter	Value
Multiresolution segmentation	Scale factor	75
	Shape	0.2
	Compactness	0.2
Spectral difference segmentation	Spectral difference	20

Table 2. Chosen segmentation parameters for the roofs

The small shape and compactness parameters of the multiresolution segmentation algorithm were chosen in order to be able to capture the individual tiles of the roof which were going to be merged with the coming spectral difference algorithm. A bigger selection of parameters would have missed the individual moved tiles. For the spectral difference parameter, a value of 20 was enough to merge the tiles into a large unit while it kept the damaged features (moved tiles) as individual objects (Figure 21).

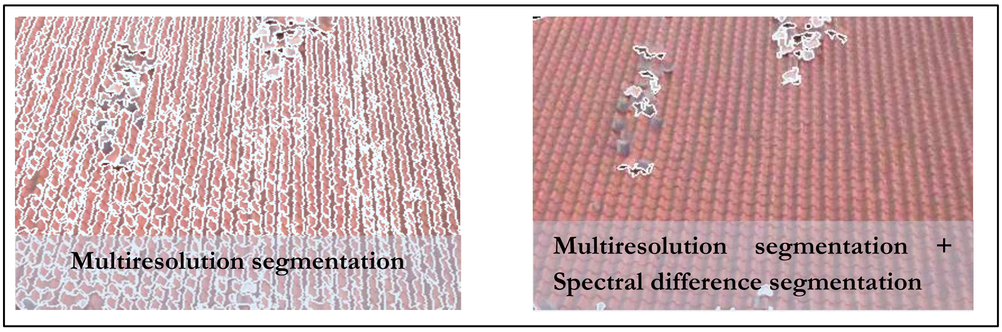


Figure 21. On the left an example of the applied multiresolution segmentation on one of the roofs. On the right, the result of applying the spectral difference segmentation on the results of the multiresolution segmentation.

2. **Classification**. The images were classified into two classes: undamaged and damaged, the last one representing the moved tiles. The area of the segmented objects was the image feature used to classify them. Assuming that the intact roof parts were going to be merged into a large intact object, by setting a threshold of 100000 pixels, the smaller image objects were classified as damaged and the larger objects were classified as intact.

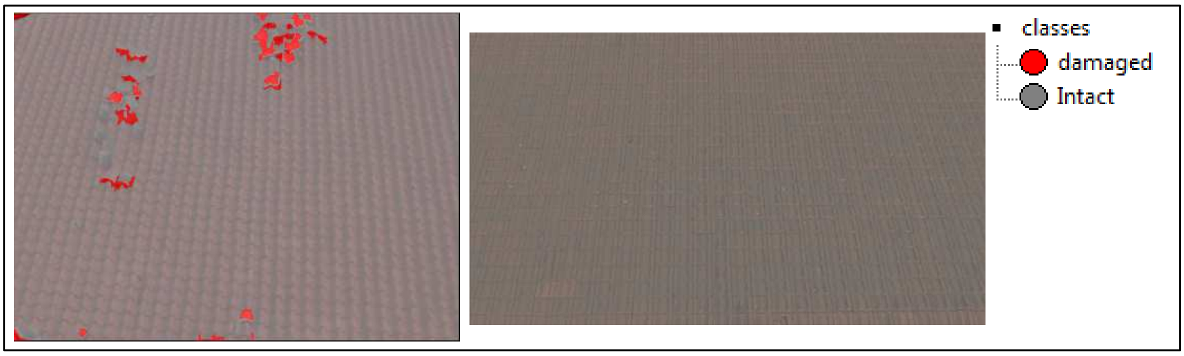


Figure 22. Examples of the results of the application of the roof ruleset in one intact roof (roof 2) and one affected roof (roof 1).

As shown in the figures above (Figure 22), the identification and classification of the damage features was solved successfully. The ruleset was tested in the two available roof images: an intact and an affected roof. As it can be seem, the ruleset was capable to find a reliable part of the moved tiles in the affected roof and it classified the entire roof as undamaged when there were no damage features to classify because the roof was intact.

Part of the tiles in the affected roof could not be captured because the spectral difference algorithm merged those objects with the undamaged ones due to being spectrally more similar to them. Although the ruleset could have been improved, one of the aims of this study was to keep the rulesets as general as possible in order to make them work in more images without having to adjust them.

4.2.2.2. Concrete façades

All the concrete façades (Table 1) were analysed with the same ruleset. The ruleset's aim was to identify the **cracks** and the **interactions of cracks with structural elements**. Concrete façades were the ones with a higher number of images in this study. For that reason, the concrete façade ruleset was the most complete and complex one. The full details of this ruleset are presented in the appendix (7.4).

This ruleset, as the one for the roofs, was divided in two main processes segmentation and classification; the last one divided in several sub-sections in order to cope with its complexity.

1) **Segmentation**. Following the same approach followed in the ruleset for the roofs, this segmentation process was done making use of the same two algorithms, the multiresolution segmentation and the spectral difference segmentation algorithms (Trimble-eCognition, 2013). In this case, the selected parameters are (Table 3):

Algorithm	Parameter	Value
Multiresolution segmentation	Scale factor	100
	Shape	0.8
	Compactness	0.5
Spectral difference segmentation	Spectral difference	20

Table 3. Chosen segmentation parameters for concrete façades.

The chosen shape and compactness parameters for the concrete façades were high, in comparison with the used for the roofs, in order to capture the big parts of the façade that were homogeneous. This selection allowed the clear identification of small cracks and, at the same time, the algorithm was able to generate big objects for the main and homogeneous intact parts of façade. Regarding to the spectral difference parameter, as with the roof's ruleset, a value 20 merged the similar objects and kept the ones that were contrasted with their background.

Although this combination of algorithms was used with the roofs, it was in this case where the qualities of this chosen combination of algorithms stood up. The aim of the multiresolution segmentation was to capture the essence of the cracks and holes in the façades; these features tended to be easily captured by this algorithm but, at the same time, it failed classifying the façade objects. The façade was over segmented, as it can be seen on the left image in Figure 23. However, it was with the use of the spectral difference segmentation when the objects really captured the essence of the damage. This happended because by merging the similar objects (Figure 23), the façade ended up been a clear big object while the cracks, due to their difference with their neighborhooding objects, were captured as different objects.

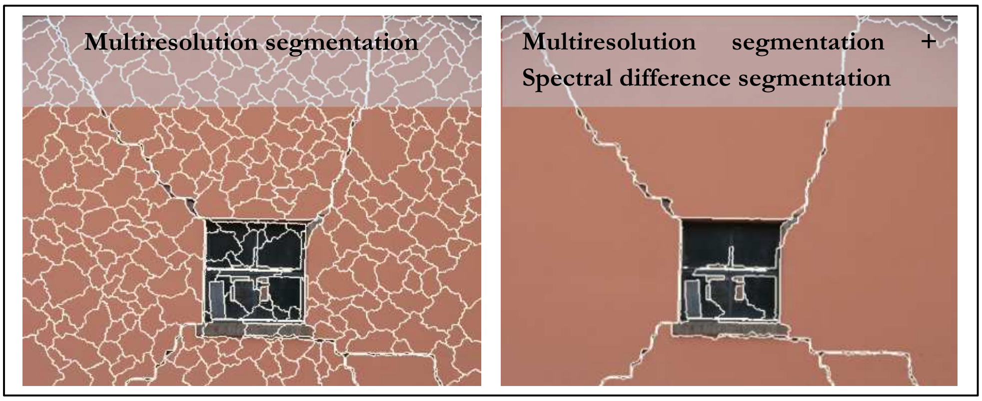


Figure 23. On the left an example of the applied multiresolution segmentation on one of the concrete façades. On the right, the result of applying the spectral difference segmentation on the results of the multiresolution segmentation.

2) **Classification.** For the concrete façades, the classification process was more complex so the classification process is explained dividing it in six sub-steps. To follow the explanation, several captures of the classification process followed in the image "concrete façade 3" (Table 15) are going to be show.

   a) <u>Windows.</u> After the segmentation process, the first and easiest elements to be classified were the windows. By using the maximum difference feature view, it was easy to identify the potential candidates. After that, and IF-ELSE statement that used the area of the object, helped to unclassified the façade objects that were classified as window but they were too big to be a window.

b) Structural elements. The second classified elements were the columns, which, due to their elongated shape, they were easy to classify by using an IF-ELSE statements that used the Length/Width to discriminate between columns and other façade objects (Figure 24).

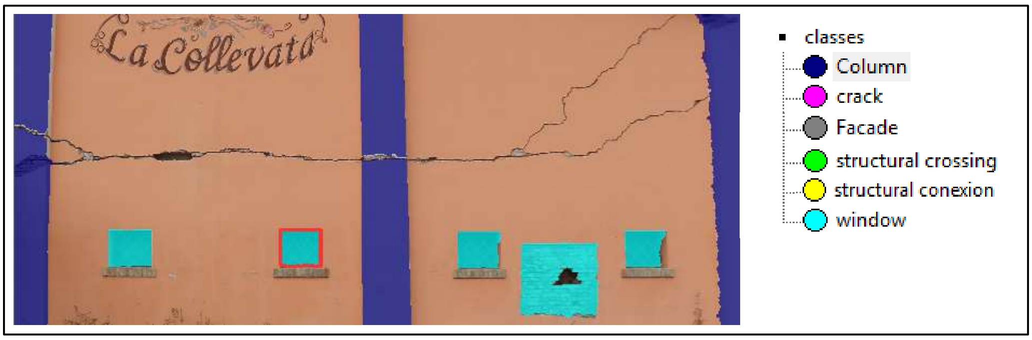


Figure 24. Capture of the "concrete façade 3" showing the results after the classification of the structural elements and the windows

c) Façade. The façades represented the main part of the images. First another IF-ELSE statement which used the relative border to window helped to get rid out of window objects that were still missclassifed. After that, all the remaining unclassified object were classified as façade. Finally, and again, to refine the window object, which many times were wrongly classified as façade, a relative border to window statement was used in the new façade objects.

d) Cracks. Finally, with all the non-damaged related elements classified, the cracks could be identified and classified. The segmentation already facilitated this task by creating those thin and compact objects. First, by using the compactness image feature applied exclusively to the façade objects, it was possible to identify the potential cracks (Figure 25).

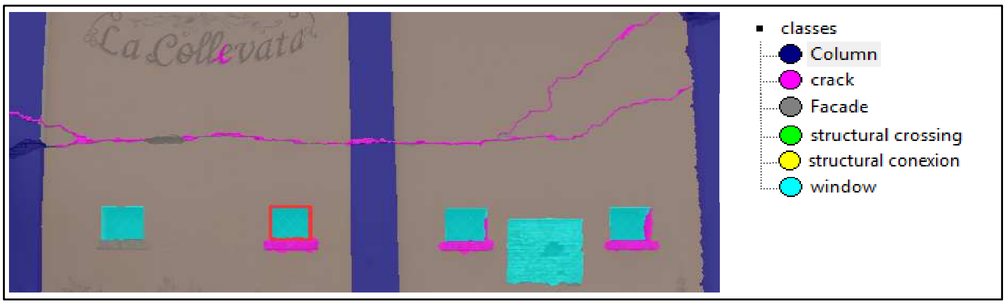


Figure 25. Result of the classification of the potential cracks in the image "concrete façade 3".

With the spotted potential cracks the refinement process started. It was composed of two IF-ELSE statements that made use, again, of the relative border to window and a multiresolution segmentation algorithm that was applied only to the potential cracks to focus the second IF-ELSE statement in the small cracks close to the windows. The refinement process' aim was to refine the crack objects that were close to the windows and that were, indeed, part of the window frame, compare the windows frame between Figure 25 and Figure 26.

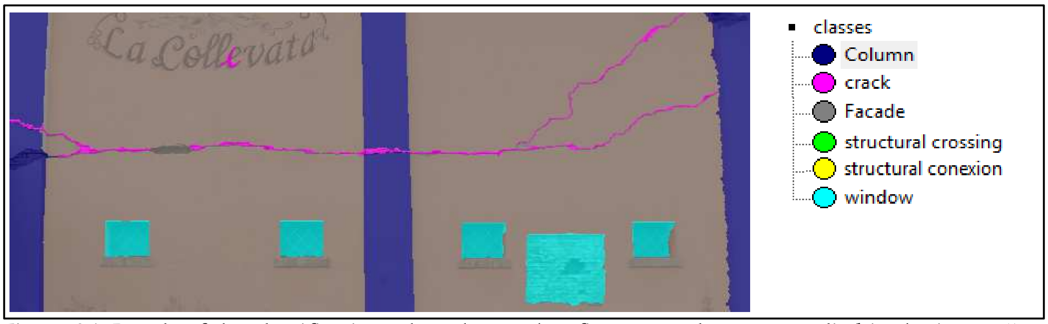


Figure 26. Result of the classification when the crack refinement rules were applied in the image "concrete façade 3"

e) Semantics. At this stage of the classification, all the objects were already correctly classified. The semantics step's aim was to identify two extra damage features that were related with the interaction of two classes: the interaction between cracks and windows and/or structural elements (columns). To classify the cracks that were crossing columns, a chessboard segmentation was applied to the cracks and then, using the relative border to columns (the only feature that can be crossed, a window cannot be crossed), with a threshold of: >50%, the crossing cracks were identified. To identify the cracks that were touching windows or columns, one again, the rel. border feature view, with a threshold of >1%, was used to identify the touching cracks (Figure 27).

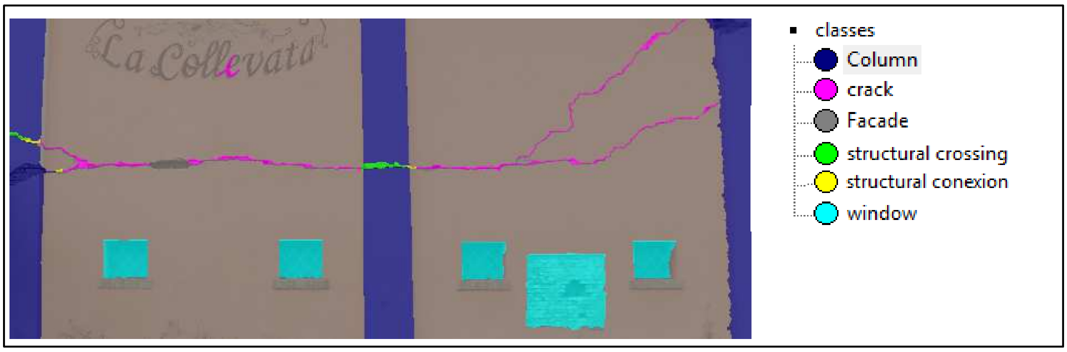


Figure 27. Results of the classification of the structural crossing and structural connexion in the image "concrete façade 3".

Each time a group of objects was properly classified; a merging algorithm was ran in order to create simpler classified segments. At the end, all the objects were merged again in order to export them as a shapefile to ArcGIS where they were ready to use by the coming steps of the methodology.

In the appendix (7.3), the classification's results that were not presented here can be found. Although some false positives, like the letter classified as a crack in Figure 27, and some false negatives, like the wide bottom crack found in the other example below (Figure 28), were found, the classifications were very accurate even in complex situations.

Figure 28. Classification result of applying the concrete façades ruleset on the image "concrete façade 4".

The overall damage classification was very adequate to the level of complexity of the concrete façades. There were simpler examples (Figure 29) where the façade, and the damage that it showed, were simpler than in the examples presented above. In those, cases the classification's result were very consistent with the damage features that the façades were presenting.

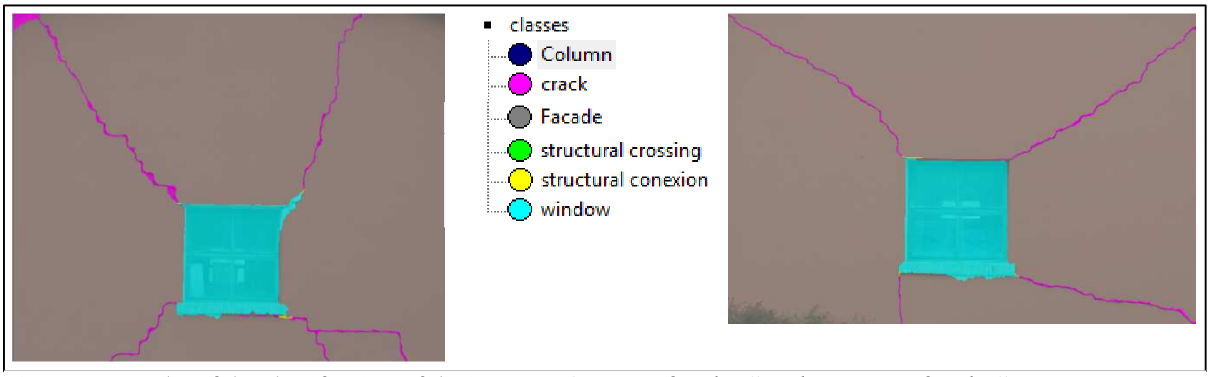


Figure 29. Results of the classification of the images: "Concrete façade 1" and "concrete façade2"

0Additionally, some of the damaged façades were edited (concrete façade 1, 2 & 4) and the damage features were erased. It was done in order to prove that, in case the algorithms were tested in a similar scenario where there were not damage, the algorithm would perform properly, not identifying any false damage feature (Figure 30). The other two examples of the classification of those edited images are in the appendix (7.3)

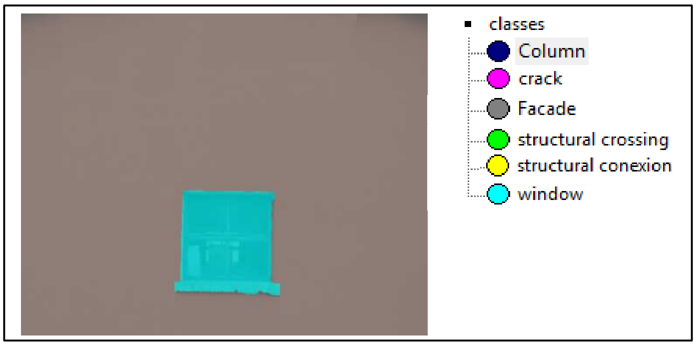


Figure 30. Result of the classification in the image: "concrete façade 1 edited"

4.2.2.3. Brick façades

All the brick façades (Table 1) were analysed with the same ruleset. Although in this case, creating a specific ruleset for each image could had leaded to more accurate results due to the differences in the scale, since one of the aims of this study was to balance between the stability of the ruleset (its capacity of being applied successfully in different images) and the amount of information that could be extracted, a single ruleset was create to classify these images.

This ruleset was made to identify **cracks**, **holes** and **interactions of cracks with structural elements** in brick façades. The assessment of brick façades was presented as a challenge due to its already complex structure made out of small bricks and concrete lines in between.

The ruleset was divided in two parts: segmentation and classification.

1) **Segmentation.** The same approach for the segmentation was followed with the brick façades. Two algorithms were used for the segmentation: multiresolution segmentation and spectral difference segmentation algorithms. The chosen parameters (Table 4) are:

Algorithm	Parameter	Value
Multiresolution segmentation	Scale factor	25
	Shape	0.2
	Compactness	0.2
Spectral difference segmentation	Spectral difference	35

Table 4. Chosen segmentation parameters for the roofs

For the multiresolution segmentation algorithm, due to its similarity with the roof patters, similar parameters to the roof were chosen. Low scale factor: 25, and low shape and compactness parameters: both 0.2. The same reason as for the roof tiles, the individual bricks were tried to be captured with the first segmentation algorithm in order not to lose any detail. In this case, the parameter for the spectral difference was higher than for the other rulesets; the heterogeneity of the bricks themselves demanded a higher value in order to merge the façade objects and highlight the objects related to damage.

Figure 31. On the left an example of the applied multiresolution segmentation on one of the brick façades. On the right, the result of applying the spectral difference segmentation on the results of the multiresolution segmentation.

The results of the segmentation in the brick façades (Figure 31) were messier than the segmentation in the other structural type or the roof. The high complexity of the brick façades generated small object that were not directly related to the damage but that could not be merged with the background, otherwise, damage information was going to be lost.

2) **Classification.** The approach followed to classify the brick façades was slightly different to the approach followed with the concrete façades. In this case the classification started with a binary classification: façade – damage, and, once the damage features were identified, a classification of those damage features was carried out. The complexity of the environment where the classification took place make the approach followed in the concrete façade unviable. To illustrate the description of the ruleset the image "brick façade 3" was used.

a) <u>Binary classification</u>. Following a similar approach to the one followed to classify the roofs, the segmentation process created a big homogeneous object which was related to the façade, and only by using the area of that object, it was possible to classify the façade and identify the rest as potential damage features. After that, the objects that were not merged by the spectral difference segmentation algorithm, were classified as potential damage related objects.

Figure 32. Result of the first binary classification carried out in the brick façades ruleset

This binary classification (Figure 32) also included a refinement process. It was meant to get rid out of the bricks that were wrongly classified as damage. To do so, the damage features were re-segmented with a multiresolution segmentation algorithm (scale factor = 20, shape = 0.9 and compactness = 0.8) that tried to capture the compact and shape-based essence and the bricks. Then with a rule that used a high rectangular fit threshold in combination with a small area, and another one that used the contrast difference of those objects with its background, it was possible to erase those wrongly classified objects.

b) <u>Features classification.</u> The damage classification started identifying the easiest damage features, in this case, the holes, which due to their area, they were easy to classify. With the holes identified all the other features classified as damage where classified as cracks, facilitating the coming improvement process.

After merging the classified objects: façade, cracks and holes, the first rule was meant to differentiate the windows from the holes. To do so, a rule that combined the rectangular fit of a window feature and its area, smaller than the one of a hole object, was used to identify windows. Although it was found successful in many cases (Figure 33), this rule was not able to identify all the windows or it identified parts of the hole as windows. In some cases, the segmentation process, focused on identifying damage features, made the windows boundaries fuzzy which obstructed their classification.

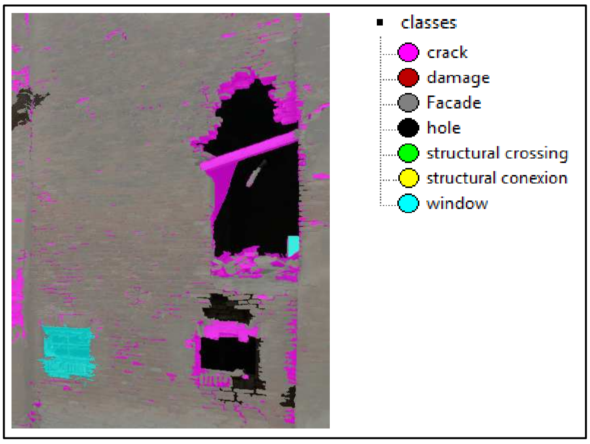


Figure 33. Result of the differentiation between holes and windows. The window on the left was successfully detected meanwhile the one on the bottom right was misclassified with a hole.

After that, a refinement process was carried out in order to get rid of all the classified crack objects which were, indeed, just the concrete lines in between the bricks. Since the concrete lines tended to be small horizontal lines between the bricks, the use a threshold of 5.6 in the feature view length/width was enough to capture and erase those longer than wider objects.

With all the features already properly classified, a semantic step, where the interaction of the damage features with the structural elements was assessed. Two were the possible combinations: the windows being touched by the cracks and the holes being touched by the cracks. For those two rules which made use of the command relative boundary to- was used. All the cracks with more than 0 relative boundary to windows or holes were classified as window structural touching.

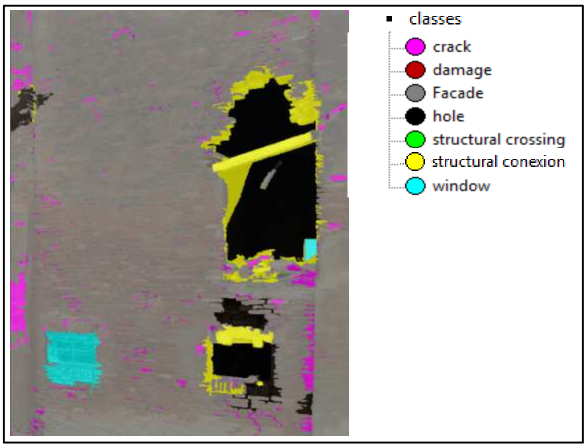


Figure 34. Final result of the classification of the image: "brick façade 3" with the brick façades ruleset.

As it was mentioned before, the high complexity of the brick façades made their classification very complicated, however the results of the classification were appropriate for this complexity (Figure 34). This described ruleset had some classification problems but it worked it three different images, the two other classified images are presented in the appendix (7.3) which represented two very different brick façades that not only implied spectral differences but scale differences.

4.2.3. Accuracy assessment

The results of the accuracy assessment of the extracted features, where the area of the extracted damaged features were compared with the area of the digitized ones, are presented in the table below (Table 5). A more detailed illustration of the accuracy assessment done, where the FN.FP and TP and overlaid on the image is presented in the appendix (7.5).

Concrete façade 1		Concrete façade 2		Concrete façade 3		Concrete façade 4	
FN	28.3%	FN	32.7%	FN	57.9%	FN	20.2%
FP	24.6%	FP	8.6%	FP	6.4%	FP	59.1%
TP	47.1%	TP	58.7%	TP	35.7%	TP	20.7%
Split factor	1.9	Split factor	6.8	Split factor	5.6	Split factor	0.3
Missing factor	0.6	Missing factor	0.6	Missing factor	1.6	Missing factor	1.0
Correctness	65.7%	Correctness	87.2%	Correctness	84.8%	Correctness	25.9%
Completeness	62.4%	Completeness	64.2%	Completeness	38.2%	Completeness	50.6%
Roof 1		**Brick façade 1**		**Brick façade 2**		**Brick façade 3**	
FN	53.8%	FN	40.6%	FN	12.4%	FN	7.6%
FP	13.2%	FP	25.5%	FP	40.7%	FP	25.5%
TP	26.4%	TP	33.9%	TP	46.9%	TP	66.8%
Split factor	2.0	Split factor	1.3	Split factor	1.2	Split factor	2.6
Missing factor	2.0	Missing factor	1.2	Missing factor	0.3	Missing factor	0.1
Correctness	66.6%	Correctness	57.0%	Correctness	53.6%	Correctness	72.4%
Completeness	32.9%	Completeness	45.5%	Completeness	79.1%	Completeness	89.8%

Roof 2		Concrete façade 1 edited		Concrete façade 2 edited		Concrete façade 4 edited	
FN	0%	FN	0%	FN	0%	FN	0%
FP	0%	FP	0%	FP	0%	FP	0%
TP	100%	TP	100%	TP	100%	TP	100%
Split factor	0	Split factor	0	Split factor	0	Split factor	
Missing factor	0	Missing factor	0	Missing factor	0	Missing factor	0
Correctness	100%	Correctness	100%	Correctness	100%	Correctness	100%
Completeness	100%	Completeness	100%	Completeness	100%	Completeness	100%

Table 5. Summary of the accuracy assessment carried out.

The split factor, a measurement that illustrates the amount of FP compared to the amount of TP, was high, above 1, in all the images except in concrete façade 4 where the ruleset detected an intact area as a crack and it affected severely the total accuracy of the extraction. The missing factor compared the amount of FN with the amount of TP. In this case the amount of missed information by the rulesets was high for the images concrete façade 3, roof and brick façade 1. There, the rulesets had some issues missing damaged areas.

Regarding to the correctness parameter, all the images seemed to have good results, except for those where the percentage of FP found was higher. This meant that, except for those images, the damage information extracted was properly correlated with the real damage found in the façade. For the completeness parameter, where the ruleset had higher false negative than the average, the completeness value went down.

It is important to notice that the percentage of FP and FN in the accuracy assessment for the images where there were not damage (concrete façade 1, 2 & 4) were 0 %. Since the ruleset did not detect damage in those images and there were no damage features to digitize, the performance of the ruleset was perfectly accurate not detecting any damage feature.

4.2.4. Demonstration of the effect of the number of rules in the stability and the amount of extracted information in the ruleset.

There is not a single or unique approach to classify an image using OOA, there could be endless combinations of rules for an image, and all of them could be perfectly valid. This means that a certain task like: "identify all the cracks in the wall", could be achieved in different ways, however, there were two factors that had to be taken into account: the hyper-fitment and the stability.

Over fitting is a common problem in OOA, which refers to rulesets that were tailor made for an image. These rulesets have rules that were exclusively applicable for that specific image because the definition of their thresholds that contained each rule were defined knowing the reliable values of the image after searching for them in a manual approach. Moreover, stability is a ruleset's property which is related to its applicability in different images, not only in the one where it has been designed. A ruleset it is said to be more stable when it could be applied to different images without tuning its parameters

A over fitted ruleset is only applicable for one image, where it would perform properly; if that ruleset is applied to another image, it would fail, it would be unstable. In the other hand, a balanced ruleset whose rules' parameters were properly defined, would be applicable to more than one image, it would be stable.

The developed algorithms for this study were meant to keep the balance in between amount of extracted information and ruleset stability. The applied rulesets in this study tried to find the balance point (Figure 35), a point where the ruleset was capable to extract most of the information from the image and, at the same time, it was applicable to several images without tuning its parameters.

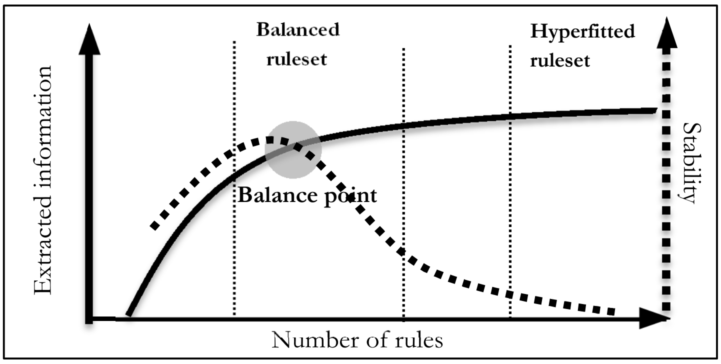


Figure 35. Illustration of the tendencies of the amount of extracted information and the stability of the ruleset at increasing number of rules.

For this experiment an extra module with 10 rules was added to the concrete façade's ruleset (Figure 36). This module consisted in a set of rules that hyperfitted the mentioned ruleset to the image "concrete façade 3".

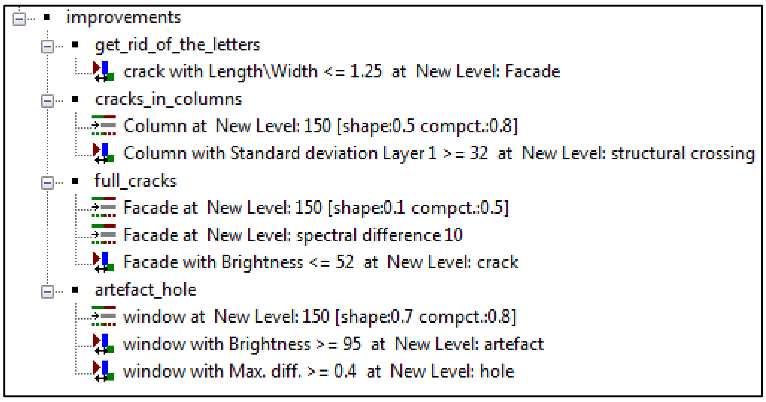


Figure 36. The ten extra rules added to the brick façades ruleset to over fit the image "**concrete façade 3**"

As it can be seen in the table below (Table 6), the over fitted ruleset behaved perfectly in the image for which it was designed (concrete façade 3), it behaved better than the balanced ruleset that had some classification issues. Regarding to the stability of the over fitted ruleset, it was low due to the misclassifications that it had in the image where it was not designed. On the other hand, the balanced ruleset kept behaving properly in the other image keeping a good amount of quality information extracted.

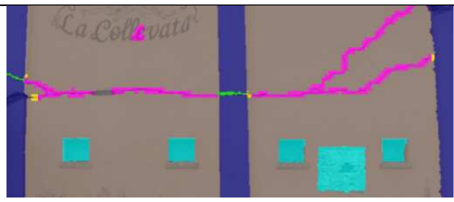
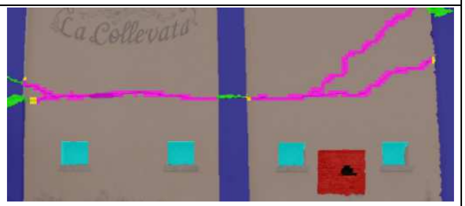
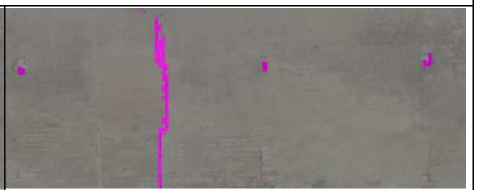
Original image	Balanced ruleset	Hyperfitted ruleset
Amount of information extracted test		
		
The ruleset is over erfitted to extract as much information from this specific image (concrete façade 3)	The balanced ruleset behaves properly although it has some issues with the letter that is identified as a crack, the missed crack part in the middle of the façade, the cracks in the lateral columns and the artefact classified as a window	The over fitted ruleset extracts all the damage information from the image. All the objects are correctly classified.
Stability test		
		
The over rfitted ruleset is not made for this image	The balanced ruleset properly identifies the two main cracks in the façade. However, it has some issues with the bottom part of the smaller crack where some false positive is identified	The over rfitted ruleset misses the secondary crack of the façade and identifies as cracks three small artefact present on the top part of the image.

Table 6. Illustration of the effect of the number of rules within the ruleset in the amount of extracted information and the stability.

4.3. The interface design and testing

The results of the previously described methodology for the interface are explained in this section. The interface, which was created in order to create an environment where the muti-perspective damage assessment could take place and where the experts could add their SDA, is explained in 5 steps.

4.3.1. Interface design and PowerPoint implementation

The interface design was a very important aspect of this section. The interface was going to be sent to several SDA experts who had no knowledge about this study, hence, the interface itself had to be self-explanatory and it had to contain enough information to make the experts understand what they had to do. The created interface was divided in:

- **Purpose and exercise explanation.** It was important to let the experts know why their help was needed and what the objectives of this study were.
- **Reasoning of the study.** In this part, several arguments that backed-up the objectives of this study were presented. The intention was to let them know that they were helping to develop something that seemed to fill the gap of the nowadays problems in the SDA.
- **Description of the EMS-98.** Although the selected experts already had knowledge in SDA, it was important to refresh the concepts that stand for the EMS-98.

- **Interface instructions.** Since the interface was not developed in a very appropriate environment, some instruction of how to interact with the PowerPoint-interface were needed.

- **Real case scenario.** This was the actual part were the experts were going to proceed with the SDA. The previously sections were meant to inform the experts about the study and how to interact with the interface. Here, the outcome of the OOA damaged extraction features was presented to the experts to proceed with the SDA.

The PowerPoint implementation was the process of creating a number of slides that simulated the designed interface. In the appendix the complete interface is included (Appendix 7.6).

4.3.2. Simulation of a real case scenario

The simulation real case scenario was the section where the experts were going to interact directly with the SDA. The simulation was meant to select several images and their classified shapefiles and connect them in order to be able to tell the story of how this interface would work. The simulation of the real case scenario can be divided into: **SDA based in a 2D environment** (description, initial 3D model, per-view SDA and wrap-up) and **SDA based in a 3D environment** (Figure 37)**.**

As it was explained in the methodology chapter, two were the approaches presenting the damage information to the experts, although only the one based on the 2D environment was going to be fully implemented while the other was just a concept. For the SDA based in a 2D environment the **description** was the part where the SDA experts could add the building type of the view they were watching. It was considered important to include an indicator of the building type since the damage was expressed differently in the different building types (1). The **3D model** was meant to provide to the experts the general view of the building and the damage it had suffered (2). The **per-view SDA** was the part where the extracted features from the OOA extraction process where presented; the expert could switch on/off the created layer in order to retrieve all the information he/she would need (3). The **wrap-up** aggregated all the presented views and the expert could go back and reclassify each façade or roof, if necessary (4). For the SDA based on the 3D environment 3D **SDA concept** was presented in a video which illustrated how the SDA would be in that environment were all the information was related to the original 3D model (5).

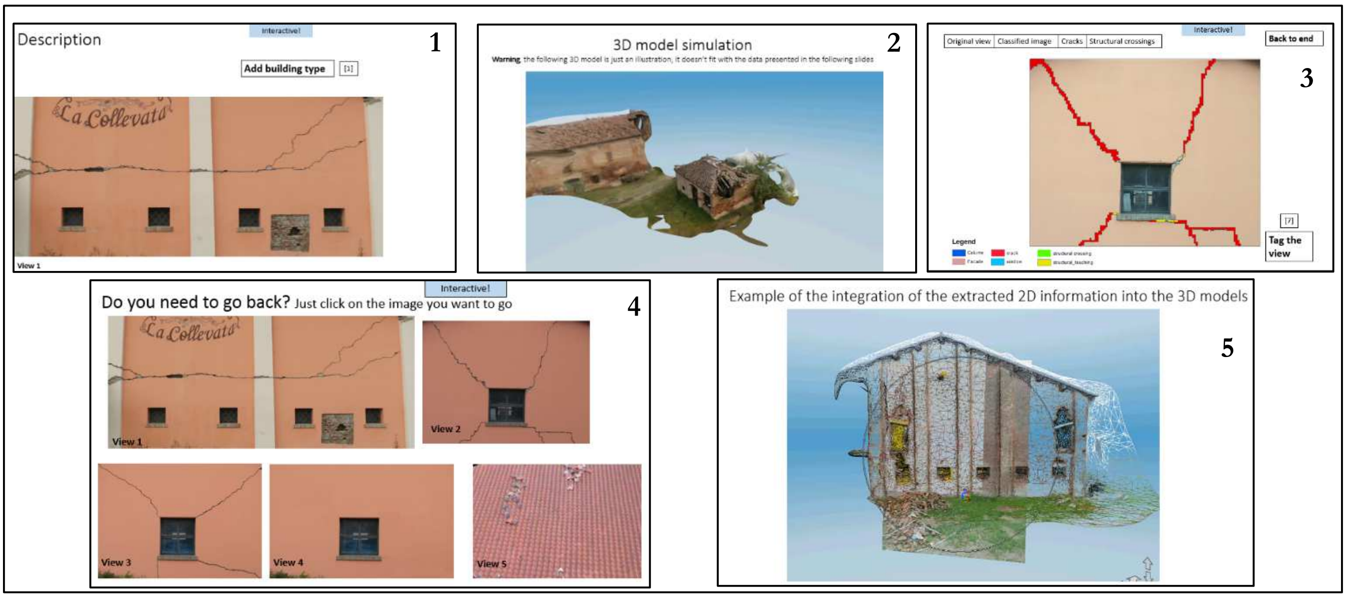


Figure 37. Captures of the PowerPoint that contains the interface exercise. 1: description, 2: 3D model simulation, 3: per-view SDA, 4: wrap up and 5: 3D SDA concept.

4.3.3. SDA questionnaire

The SDA questionnaire was an attached txt file that was included within the interface. This txt file stored the questionnaire that the expert had to fill in to complete the SDA and give the feedback about the interface. The information that the experts had to provide can be grouped in the following way:

- **Description information.** In this part, the experts had to define the building type of the façade that they were watching. The options were: brick façade, concrete façade or roof.

- **Structural damage assessment information.** This was the part where the experts had to use their expertise in order to classify each view with the damage score that they considered. The damage score could go from D1 to D4 for the façades and from D1 to D3 for the roofs (Table 7). Besides the damage score, the questionnaire also included a certainty measurement. This certainty measurement was a number from 1 to 3 being 1: uncertain, 2: quite certain and 3: very certain (Table 7). This extra information, that was not considered in other SDA studies, was meant to add a quality measurement to the final per-building damage score which could indicated how certain the expert was of its classification.

Damage score	EMS-98	Certainty measurement	Value
Negligible to slight damage	D1	Uncertain	1
Moderate damage	D2	Quite certain	2
Substantial to heavy damage	D3	Very certain	3
Very heavy damage	D4		

Table 7. The different levels of damage scores and certainty measurements allowed to be used in the interface

- **Usability assessment.** A set of 8 questions, which are presented below, were asked to the experts. These questions tried to address the usability of the interface. With these question, the idea was to gather the insight of the experts that would help to improve the approach of the interface by identifying weak, missed and unclear points in the interface.

  a) Although the 3D model doesn't match with the data presented, Do you think that it is good to have an overview of the situation before addressing the assessment of each one of the view?
  b) Do you think that the 3D model that is presented before the 2D images has already biased your mind to a certain EMS-98 score?
  c) Do you find useful the overlaid information in the 2D images?
  d) From the presented overlaid information , Which one do you think it is more helpful? Damage, cracks or structural crossings.
  e) Can you think in other information that might be useful for the assessment?
  f) Do you think that this interface helps you to produce more reliable damage scores per-façade or per-roof?
  g) Taking into account that the damage assessment is done for each façade and roof, Do you find useful or a better approach to present the information directly in a 3D model?, like in the last video, or Do you prefer to work in "isolated" views of each façade and roof?
  h) Would you like to add any suggestion or comment that was not addressed with the questions above? Feel free to explain what you would like to add.

4.3.4. Visualization of the extracted damage information

The results of the methodology followed to create these two visualization are the following.

2D based approach

Although the damage assessment was based in the 2D images, this approach also included a 3D model that gave the overview of the damaged building to the experts (Figure 38). By using 123D Catch (2013) to create the 3D model from the overlapping images, the result was a realistic and dynamic model of the building. In the interface this 3D model was included as a video due to the impossibility of including an interactive 3D environment within PowerPoint.

Figure 38. Capture of the video presented in the interface that contained the 3D model visualization

Then the extracted features from the OOA extraction process that were stored in a shapefile in ArcGIS were overlaid with the real images. Four different layers were created: **original view, classified image, cracks** and **structural crossing**. Those represented the most reliable damage features extracted that were useful for a complete SDA. Examples of the different layers are presented below in Figure 39.

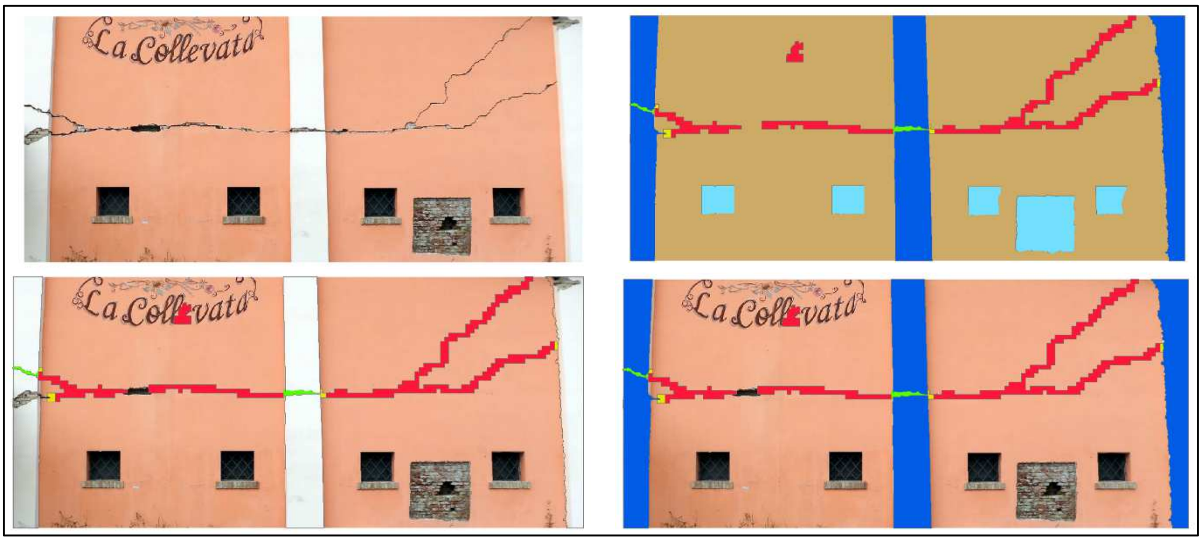


Figure 39. . Top-down and left-right: Original view, classified view, cracks view and structural interactions view

3D based approach.

The process to create the 3D visualization started similar to the process followed in the 2D approach. A 3D model had to be created using 123D Catch (2013) (Figure 40).

Figure 40. View of the original 3D model

With the 3D model ready, the classified images had to be exchanged by the original ones that were stored in the 3D model. With the classified images already in the folder of the 3D model, they could be visualized in the 3D space (Figure 41).

Figure 41. The two overlaid classified images on the 3D models. Grey colours for the undamaged parts of the façade, yellow for the holes and red for the cracks

4.3.5. Summary of the received feedback

As mentioned, one of the outcomes of the interface part were a set of real SDA and the answers of the questions that were asked in the questionnaire.

The interface was finally tested by 6 experts on different fields related to SDA (Appendix 7.8). Their damage scores, certainty measurements and feedback, were very valuable to understand how they proceeded and perceived the proposed approach for SDA. In the following table (Table 8), the damage scores and the certainty measurements are presented.

Damage scores					
Expert	**Façade 1**	**Façade 2**	**Façade 3**	**Façade 4**	**Roof**
Expert 1	3	3	2	2	1
Expert 2	2	2	1	1	1
Expert 3	3	3	3	1	2
Expert 4	3	2	2	1	3
Expert 5	3	3	3	1	1
Expert 6	2	3	2	1	2
Certainty measurements					
Expert	**Façade 1**	**Façade 2**	**Façade 3**	**Façade 4**	**Roof**
Expert 1	3	2	2	3	3
Expert 2	2	2	2	3	2
Expert 3	2	2	2	2	2
Expert 4	3	3	2	2	1
Expert 5	2	2	2	1	1
Expert 6	1	1	1	2	1

Table 8. The collected damage scores and certainty measurements from the 5 experts that collaborated on the interface test. Damage scores, from the possible 1 to 4, orange corresponds with level 3, yellow with level 2 and green with level 1 (Table 7). Certainty measurements, from 1 to 3, green corresponds with level 3, yellow with 2 and red with 1 (Table 7).

The main conclusion extracted from their feedback were:

- The 3D model presented before the individual analysis of the façades and roof was useful for them in order to observe the damage in their context. Besides, they all agreed that this 3D visualization did not bias their posterior façade/roof assessment.

- The experts pointed out that the presentation of the extracted damage features by OOA did not add greater insight than the visual interpretation of the image itself. Except for the features that highlighted the interaction between the damage features and the structural elements.
- There were experts supporting the two approaches to visualize the damage features. Some experts said that the individual view of each façade were necessary to proceed with a reliable SDA, and other experts argued that the visualization of the features directly in a 3D environment would help them to produce more reliable damage score per-building.

4.4. Aggregation of the multi-perspective damage information

This step of the methodology was meant to aggregate the damage and certainty information, which at this stage was referred to each façade and roof of a given building. The aggregation process comprehensively summarized that information to a building level. The aggregation of the multi-view damage scores was done in 3 step: **simulation of the expert SDA per-façade/roof scores**, **development and implementation of the algorithms** and **algorithms test**.

4.4.1. Simulation of the experts SDA per-façade/roof scores.

Due to time and data constrains, the amount of real expert SDA was limited, so, in order to be able to test how the aggregation algorithms were going to work, a set of randomly simulated SDA had to be created. It is important to mention that the created simulation were not perfectly realistic; they were a random simulation, they were created just to prove that the algorithms could cope with a similar scenario.

Two tables were created in R-Studio: one table for the damage scores (Table 9) and one table for the certainty measurements (Table 10), each table with 100 simulations.

- Simulated damage scores

For the damage scores, the table was organized in 5 columns: façades 1 to 4 and roof. The values that could be stored in each column went from D1 to D4 for the façades and from D1 to D3 for the roofs. Regarding to the EMS-98, a D4 building implied parts of the roof collapsed, which, according to the developed methodology, these kind of roofs would have been identified in the 3D point-could assessment and, therefore, such a building would have not reached this part of the methodology because it would have been classified as D4 in the first part of it. An illustration of the simulated damage score table (Table 9) is presented below.

	façade1	**façade2**	**façade3**	**façade4**	**roof**
House 1	4	3	2	3	2
House 2	4	1	4	4	1
House 3	1	2	2	1	1
House 4	2	3	3	3	3
House 5	2	2	4	4	3

Table 9. First 5 randomly assigned damage scores for the 5 views taken into account

To simulate the damage scores the code presented in the appendix (7.7) was used. To generate the random sets of scores the function "sample" was used.

$$\boldsymbol{sample(x: y, n, replace = TRUE)}$$

x:y => Defined the range of possible numbers that could be introduced in the column
n => Referred to the number of values that had to be created
replace =TRUE => Specified that a value could be repeated within each sample

- Simulated certainty measurements

For the simulation of the certainty measurements the same approach was followed, although in this case all the columns could have the same range of values from 1 to 3: 1:uncertain, 2: quite certain and 3: very certain. An illustration of the simulated table is presented below (Table 10).

	façade1	façade2	façade3	façade4	roof
House 1	1	3	3	1	1
House 2	3	3	3	2	2
House 3	2	2	3	2	1
House 4	1	3	3	1	1
House 5	1	3	1	1	1

Table 10. First 5 randomly assigned certainty measurements for the 5 views taken into account.

To simulate the certainty measurements the code presented in the appendix (7.7) was used:

Creating this simulated expert's outcome, a conscious simplification of the reality was made: no weighting was applied to the damage scores. It implied that the presence of a D3 façade did not imply that the adjacent façade had to be, most likely, in between D2 and D4, which is what happens on the field. On the field an entire building, of the same building type, is affected by the same forces producing similar damage in its façades and roof.

4.4.2. Development and implementation of the aggregation algorithms

This step was a key point in the methodology because, up to now, there was no approach where the damage information collected from each façade and roof a building, would have been understood and then aggregated into a single per-building damage score. In order to keep the process simpler two algorithms were created: one to aggregate the damage scores and another to aggregate the certainty measurements.

- Damage scores aggregation algorithm.

First, the reasoning behind the algorithm had to be described and then it had to be implemented in R-Studio. The created algorithm followed a top-down approach which first addressed the higher levels of damage and then it went down looking for lower damage scores. This algorithm was meant not to underestimate the damage evaluation of a building, for that reason a higher weight was given to the D4 elements which had the priority in any possible situation. The created algorithm can be summarized in the following table (Table 11).

Per-façade/roof damage score	Per-building damage score
One or more D4 evidences	D4
> 50% of the façades are D3	D3
< 50 % of the façades are D3	D2
> 50% of the façades are D2	D2
< 50% of the façades are D2	D1

Table 11. Description of the algorithm created to aggregate the per-façade/roof damage score in the building level

The implementation of the algorithm in R-Studio was done using a set of IF-ELSE statements. The code used is presented in the appendix (7.7):

- Certainty measurements aggregation algorithm.

For the aggregation of the certainty measurements of the per-façade/roof classification, a simpler approach was followed. The aggregated certainty measurement had to represent the certainty that led to the final per-building damage score, and for that, all the certainty measurements had to be taken into account. The equation that aggregated the set of values is presented below:

$$((\sum \textit{certainty measurements}) * 100)/15$$

The presented equation scaled the total certainty of the classification in a percentage that could be easily interpreted. The code used to integrate that operation in R-Studio is presented in the appendix (7.7)

4.4.3. Algorithms test

The two aggregation algorithms were run through the date frames making use of a repetition function in R-Studio. The outcome of the aggregation process was stored in two data-frames: aggregated damage scores and aggregated certainty measurements. A illustrations of how the scores were transformed are presented below (Figure 42 & Figure 43).

Damage score aggregation algorithm

Damage scores					
	façade1	**façade2**	**façade3**	**façade4**	**roof**
House 1	4	3	2	3	2
House 2	4	1	4	4	1
House 3	1	2	2	1	1
House 4	2	3	3	3	3
House 5	2	2	4	4	3

Aggregated damage score	
House 1	4
House 2	4
House 3	2
House 4	3
House 5	4

Figure 42. Illustration of how the first 5 sets of damage scores were aggregated into a single per-building damage score

Certainty aggregation algorithm

Certainty measurements					
	façade1	**façade2**	**façade3**	**façade4**	**roof**
House 1	1	3	3	1	1
House 2	3	3	3	2	2
House 3	2	2	3	2	1
House 4	1	3	3	1	1
House 5	1	3	1	1	1

Aggregated certainty measurements	
House 1	60%
House 2	86%
House 3	66 %
House 4	60%
House 5	46 %

Figure 43. Illustration of how the first 5 sets of certainty measurements were aggregated into a single per-building damage score

In the appendix (7.7) the aggregation of both complete tables (Table 17 & Table 18) is presented, including the code used in order to proceed with the entire simulation.

As it has been illustrated above, the algorithms were able to aggregate the multi-view damage related information into a building level. The transformation done in the certainty measurements was minimum, the algorithm just calculated the mean of the certainty measurements and it presented it as a percentage. Therefore, the visualization of the overall aggregation process (Figure 44) did not presented any patterns.

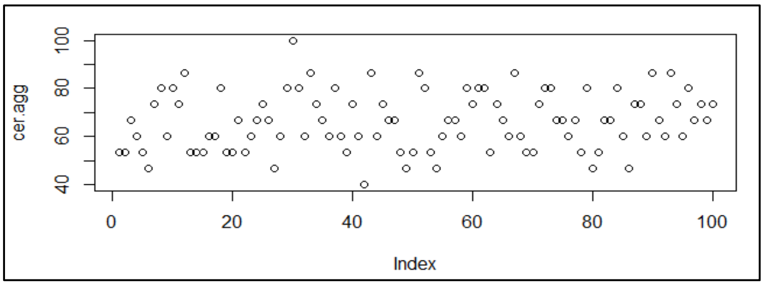


Figure 44. Graphical representation of the distribution of the aggregated certainty measurements

In the case of the aggregation of the damage scores, the visualization of the overall aggregation did show a reliable pattern. As can be seen below (Figure 45), most of the buildings were classified as D4. Part of this effect was related with the random nature of the simulated scenario, which made that most of the rows contained at least of façade classified as D4. The other part of the effect had to do with the importance that was given to the D4 façades in the aggregation algorithm, The algorithm was designed to classify the entire building as D4 as soon as, one of its façades was classified as D4.

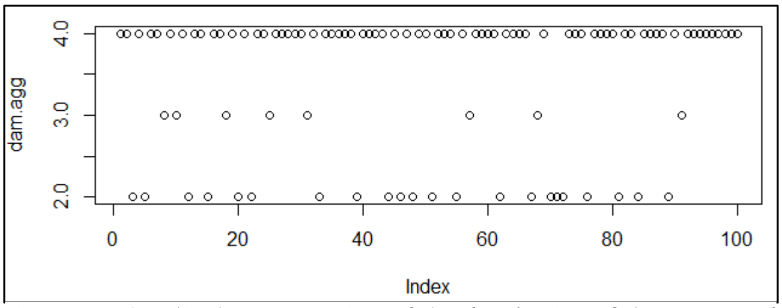


Figure 45. Graphical representation of the distribution of the aggregated damage scores.

The results of the aggregation process of the real expert outcome were the following (Table 12).

Expert	Aggregated damage score	Aggregated certainty measurements
Expert 1	2	86 %
Expert 2	1	73 %
Expert 3	3	66 %
Expert 4	2	73 %
Expert 5	3	53 %
Expert 6	2	40 %

Table 12. Result of the aggregation of the real expert outcome.

As it can be seen, three of the expert, according to the damage aggregation algorithm, understood that the building was a D2, one understood that it was a D1 and other one understood it was a D3. Regarding to the aggregated certainty measurement, all the experts proceed with low uncertainty, except experts 5 and 6 who classified the entire building with more perceived uncertainty.

The results chapters has described objectively the outcomes of the developed methodology: the evidences found in the 3D point-cloud to classify entire buildings as D4 or D5, the list of reliable damage features, the rulesets to extract them, the accuracy assessment, the illustration of the effect of the number of rules within the ruleset, the whole interface and its testing outcome and the developed aggregation algorithms and their R-studio environment where they were tested.

5. DISCUSSION

This discussion chapter in meant to explain the problems and limitations found during the application of the proposed methodology, and to explain more in detail the conflictive points that have been reached. This chapter was divided in the same four big sections described in the results.

5.1. 3D point-cloud assessment

It was clear that the visual proofs presented in the results section demonstrated that the assessment of 3D point-clouds can provide enough evidences to identify the features that would classify an entire building as D5 or D4. However, in that section, only examples of what can done were presented. In fact, the 3D point-cloud assessment carried out, only used the visual interpretation of the z-component to point out the presence of those evidences in the point-cloud, there were not automatic techniques applied. For future studies, this part of the methodology should be revised and understood more in depth.

5.2. OOA damaged features extraction

5.2.1. Damage features selection

The selected damage features that were going to be extracted by OOA were found reliable and representative of the damage that could be seen in the façades and roofs of a buildings. However, this damage catalogue was limited to the basic damage features that could be found in-the-field. The complexity of the damage features that a building could present are related to several factors such as: building type, earthquake's shaking directions, soil type, etc. The most conventional damage features that could be found were the selected ones: **cracks**, **holes**, **their interactions with the structural elements** in the façades and **moved tiles** on the roofs, however, many other features like spalling walls, deformation of columns or different types of cracks, such as dislocation cracks, were not included in the catalogue. To keep a basic damage features catalogue was decided in order to not to include too many features in the rulesets, that were going to increase their complexity, and at the end, their presence on the building were less representative and more building type specific.

It has to be noted that the selected damage features for the OOA extraction were the ones that could be present in the building from D1 to D4. Another set of damage features more characteristics of D5 and D4 buildings, such as rubble piles or inclines walls, was already addressed in the 3D point-cloud assessment part, reason why they were not part of the mentioned damage catalogue for the OOA feature extraction.

5.2.2. OOA extraction rulesets

The three different developed rulesets were designed to capture the previously defined damage features. The results of their extractions (Appendix 7.3) were satisfactory for the three cases, taking into account the level of complexity of the images were they were tested. It is important to notice that the each one of the three ruleset was applied on different images and they performed according to the plan without any parameter tuning. The discussion of the OOA extraction ruleset is done according to their two main bodies: segmentation and classification.

a) Segmentation.

In the three rulesets: roofs, concrete façades and brick façades, the approach followed for the segmentation was the same. A multiresolution segmentation was applied to capture the damage features and it was followed by spectral difference segmentation whose aim was to merge the similar object generated in the previous segmentation and highlight the damage features that, now, were perfectly differentiated from other non-damage related objects. This approach was proved to capture the essence of the damage in the images but it also showed how in certain situations, part of the damage elements were merged with the non-damage related objects. This situation was found in the roofs, where some of the moved tiles were merged with the intact roof (Figure 21), and especially in the bricks façades, where in order to capture the bigger cracks, many smaller and thinner cracks were merged with the façade and at the same time some artefacts (Figure 46) of the façade remained as independent and potential damage related objects for the ruleset.

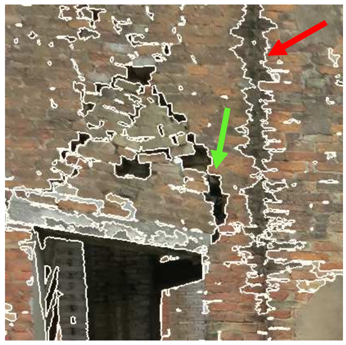


Figure 46. Green arrow pointing out an object that captures a damage feature, the red arrow points a no damage related object

Although many of these situations were found after the segmentation processes, the key point was to have found that the combination of that a multiresolution and a spectral difference segmentation algorithms was as very useful approach to capture the damage. It can be said that the combination of this two algorithms was meant to highlight the inhomogeneous elements in the façades and roofs, elements which tend to be related to damage (Dell'Acqua, 2013).

b) Classification.

The classification process followed the segmentation step and it met the requirements of providing a meaning to the objects that were created after the segmentation. The three sets of rules, were able to identify the reliable damage features in all the images where they were tested. However, due to the complexity of the images, and the aim of keeping a single rulesets per façade building type and roof, some conscious concessions had to me made. These simplifications had a direct effect on the final classification where, as it can be seen in the appendix with the final results of the classification (Appendix 7.3), the three algorithms failed somewhere misclassifying some damage elements, missing damage elements or wrongly classifying as damaged objects that were not damage related. Illustrations of this errors are:

- The moved tiles that were wrongly classified as "intact roof" in the image "roof 1"(Figure 49).
- The letter in the concrete façade of the image "concrete façade 3" that was identified by the algorithm as a crack when it was just part of the decoration of the façade (Figure 48).
- The elements found on the brick façade that were identified as cracks by the algorithm when they were, in fact, just a plaster artefact in the image "brick façade 2" (Figure 47).

Figure 47. Example of missed moved tiles

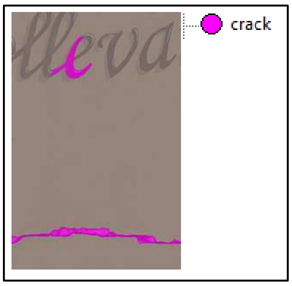


Figure 48. Example of a letter classified as a crack in a concrete façade

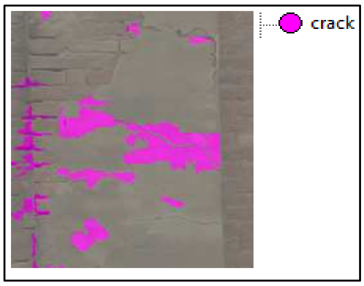


Figure 49. Example of a plaster artefact classified as a crack in a brick façade

Some of these errors could be found in the final classification results, however, the weight of these errors was low in comparison with the fact that a single ruleset was able to achieve those reliable classifications in different environments without the tuning of its parameters. Besides, roofs and concrete façade do not have that many errors as the brick façades, it is important to remember that the nature of the bricks façade was already very complex due to their elaborate brick configuration.

Moreover the classification of the damage features, it was also important the interpretation and the meaning that those elements had. The identification of the interaction of the cracks with the other elements was an important step to clearly identified problematic parts of the façades where the damage elements were crossing or connecting with structural elements (Figure 50).

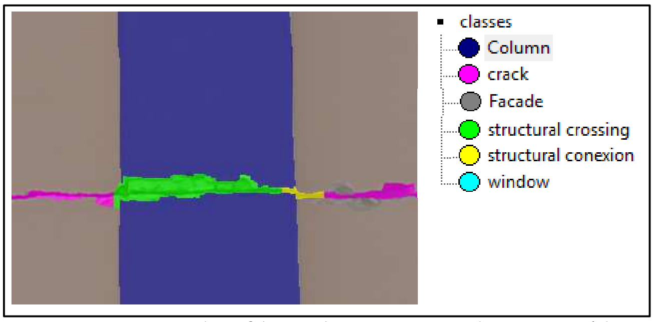


Figure 50. Example of how the concrete ruleset was able to identify a crack that was crossing a column

The bricks façades, as it has been mentioned before, were more complex than the roofs, where only one damage feature had to be classified, or the concrete façades, where the façade configuration itself facilitated the classification of the damage features. Besides that, another challenge for the bricks façades showed up, this challenge had to do with the different scale of the images were it was tested. The brick ruleset was tested in three images, two of them from Italy (brick façades 2 & 3) and one from Gronau (brick façade 1). The two images from Italy had a similar scale while the image from Gronau was taken from much closer, which increased the scale of the picture and the elements (the bricks) seem to be bigger (Table 15)

This issue was the reason why many of the small object that were identified as crack in the images "brick façade 2 &3" could not be erased by just simply using the area of those object to get rid out of them. When this was tried, the artefacts in the Italian brick façades could be erased but it also erased the real crack objects in the Gronau's façade. In Figure 51 the red arrow points out to the part of the crack that would be missing after applying that rule to erase the artefacts in the italian brick façades.

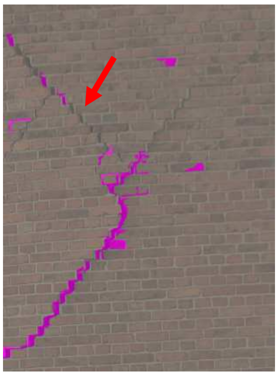


Figure 51. The red arrow points out to the part of the crack that is missing

5.2.3. Accuracy assessment

The accuracy assessment showed the relation between the area of extracted features and the area of reference dataset that was digitized. For that, several statistical measurements where calculated and their meaning was already explained in the previous chapter. However, the weight and reliability of the accuracy measurements were relative for this study.

For this study, where the importance was to identify and classify the objects which were related to damage features in the façades and the roofs, and accuracy assessment based on the comparison of the areas was not very meaningful. Indeed, the problem was that there was not a proper accuracy assessment technique that really represented the accuracy of the damage features extraction whose value was the meaning. Since the damaged features extraction was meant to highlight the damage and therefore, to facilitate the SDA of the experts when they were dealing with each one of the façades, it was complicated to really capture the accuracy of the extracted features by comparing their area with the reference dataset.

As an example of the complexity of the accuracy assessment the already used example of the letter is used (Figure 52): in the image "concrete façade 3" there was one letter in the façade that was wrongly classified as a crack. The area of that crack, counted as a False Positive, and had a number of effects on the calculated statistical measurements: the split factor and the correctness decreased. However, that false positive did not have such an importance for the end-users who were carrying out the SDA for that façade, none of them made any comment regarding to this in their feedback.

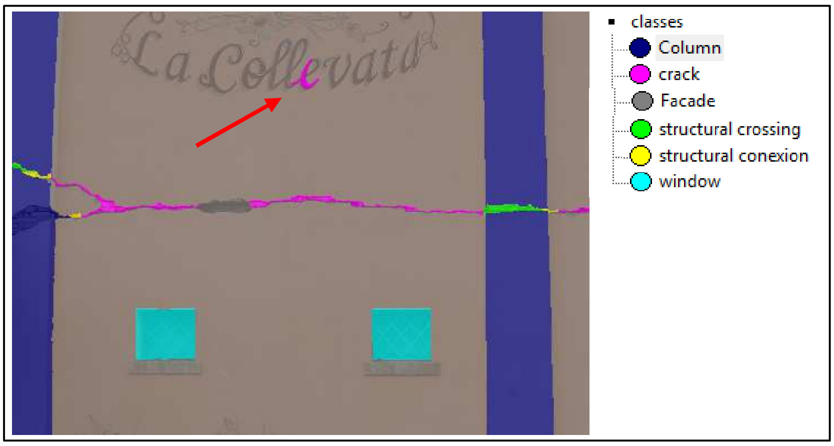


Figure 52. Example of the concrete façade where the ruleset detect a letter as a crack (red arrow) which counted as a false positive for the accuracy assessment.

This accuracy assessment was done because it was understood that the extraction of the selected damage features had to be compared with the real damage features presented in the images, however, more research would be needed in order to design an accuracy assessment that could capture the essence of this extraction process which was, indeed, more related with the semantic meaning of the extracted features.

5.3. The interface design and testing

The interface was created to show to the experts on SDA a simulation of how this study proposed to present the extracted information in the previous step by creating an environment where the multi-view SDA was enhanced and to see if it would help them to carry out more reliable SDAs. The interface achieved these tasks and it was successfully used by several experts who were able to go through the interface and provide with their assessments on the simulation that was presented to them. However, the interface would need more improvements and a more proper environment needs to be developed in the future.

Many assumptions were made in order to create this interface and they have to be further discussed:

- In the field, the visible façades that contained damage features were registered, but some of the façades of those building could not be captured due to fencing issues. For this reason, the simulation of a real scenario had to be made with façades of different buildings that were assumed to be part of one building. Besides the 3D model, that was meant to complement the real case scenario, did not match the selected 2D images for the same reason.
- The building that was evaluated was be made out of 4 façades and one roof. This is a reality that can be found in the field, but it is also very likely to find bigger buildings that would need more than one image to cover each of their façades. It is understood that this was a simplification of the reality, but, due to the endless scope of possibilities that could be thought of, this decision had to be made and kept for the rest of the study.

Besides the assumptions presented above, some other points have to be discussed. i) The ancillary information provided with the interface in order to explain the interface, was found useful by the experts to understand what they had to do. ii) Regarding the two approaches for the visualization of the damage features, although the interface was developed based in the 2D images, the experts coincided in the potential of the visualization of the damage features in the 3D space where they would be able to understand the damage in its context. This would also overcome some issues found by some experts that pointed that the use of images where the façade was not completely visible was a constraint for them to understand the extent of the damage and, hence, a constraint to provide accurate damage scores. This means that in future, for the studies related to the visualization of per-façade/roof damage features, the information should be presented directly in a 3D environment.

A summary of the comments obtained from the expert was presented in the results section, however, in this section, the focus was to proceed with a more extensive discussion and argumentation of their feedbacks. The main points of discussion were: i) the low importance given to the overlaid information of the damage features, ii) the problems related to the extension of the views presented in the interface, iii) the use of the EMS-98 for a per-façade/roof SDA and the lack of an algorithm to aggregate those per-view EMS-98 scores, iiii) the issue regarding to the type of imagery used and iiiii) the potential of this study towards a fully automatic SDA.

i) For the experts, such an interface, where some extra damage information was overlaid on the raw imagery, would not be too useful to improve or to generate more reliable damage scores, as it was assumed in the methodology. A comment was that they only needed the raw imagery in order to classify the image. However, it has to be noted that the testers of the interface were already very well trained experts in the field of the SDA, which means that they had done many in-the-field surveys were the only use of their knowledge was enough for the damage assessments. A possible comment would be that this interface could be used to help to less experience personal to produce as reliable SDAs as the personal that already have experience on the field.

ii) Another comment which was found in two of the six feedbacks was that the presented views in the interface did not cover the entire façades and hence, they could not understand the total extension of the damage on the façades. Therefore, they said that their final per-view classification could be wrong due to the lack of extension understanding. This point was related to the fact that, in order to reduce the complexity of the images towards their OOA damaged features extraction, the images where cropped to focus the analysis in the actual façade and roof areas. In future studies, the interface should present the entire image with the overlaid extracted damage features, even if the OOA extraction process is done in a shrunken version of the original image.

iii) In the feedback of the interface, there were also some comments regarding to the use of the EMS-98 for per-façade and per-roof SDA. The experts commented that the EMS-98 is a scale whose aim was to generate per-building damage scores and, hence, it would not be too valid to produce per-façade/roof damage score because the description of the features that addressed the EMS-98 were meant to be checked in the entire building. However, as mentioned in the introduction, the EMS-98 has been used in many remote sensing studies besides its known limitations for vertical (or oblique) single view imagery where only one side of the building, not the entire building, was used to proceed with the damage mapping. For this reason, and because in the documentation of the EMS-98 (1998) it was possible to differentiate the characteristics that described the different damage levels in between the ones referred to façades and the referred to roofs, for this study the chosen approach was focused on classify each façade and roof within the EMS-98.

Besides, one of this experts pointed out that there was not an algorithm to aggregate the per-façade/roof EMS-98 damage scores into a per-building level. Indeed, this study proposed one algorithm to aggregate this information because this issue was noticed in advance.

iii) One of the experts mentioned that she/he was surprised by the imagery presented in the interface because he/she was expecting more oblique kind of imagery. Indeed, the imagery presented in the interface was taken with an 8 m pole and a camera attached to it that was meant to simulate the UAV flight. However, the images taken with this technique were similar to the kind of image that UAV could take when its main goal is to map the façade. The illustration below (Figure 53) presents an example provided by the PhD candidate in the University of La Sapienza Ms. Martina Mormile, that proved that the imagery present in the interface and used in this study simulated the imagery that could be taken with a UAV.

Figure 53. UAV image of a façade in Italy (2012)

iiii) The last discussion point addressed that this study, with the features that had been extracted, could be self-efficient to carry out a fully automatic SDA. Such a scenario would not be far from the current reality, although due time constraints it could not be included in this thesis. However, it is possible to show a very simple translation table for the façades (Table 13) that would translate the presented features in the façades to the EMS-98 (Table 14). Indeed, after the aggregation of the façade damage scores, according to the proposed algorithm, the per-building damage score would coincide with the average response from the experts: D2 (it was possible to make this assumption without considering the roof because even if the roof was a D3, the final score would have been D2). To include the roofs would be slightly more difficult since the difference in between D1 and D3 would be related only the amount of moved tiles and that would need further analysis.

Presented feature	EMS-98
No damage features	D1
Simple cracks	D2
Cracks crossing structural elements	D3
Holes	D4

Table 13. Simple translation of the presence of certain damage feature in the façades to the EMS-98 classification.

Interface view	Presented feature	EMS-98
	Cracks with interaction with structural elements	D3
	Simple cracks	D2
	Simple cracks	D2
	No damage features	D2

Table 14. Example of the application of the proposed translation rules on the façades presented in the interface.

5.4. Aggregation of the multi-perspective damage information

The aggregation of the multi-view information regarding to the damage and the certainty of the classification was done successfully. It was possible to first create a set of randomly generated simulation of the outcome of the interface to counteract the lack of real expert outcome, then develop two different algorithms to comprehensively aggregate that information, and finally, the algorithms were tested with that simulated outcome and the real outcome, which allowed to infer some conclusion of their performance.

5.4.1. Simulation of the experts SDA outcome

It was known that the approach to simulate the SDA outcomes was not too realistic, the main simplification was that the in the generation of the score, each façade had the same probability of having any of the 4 possible damage scores (D1, D2, D3, D4) independently of the score of the adjacent façades. This was a simplification because, in-the-field, the same building with the same structural types, would experiences the same shaking and, hence, all the façades would be supposed to show similar damage features. However, although it was known, the main aim of the simulated dataset was to recreate a dataset to see if the algorithms that were created to aggregate that information had a proper performance.

5.4.2. Development and implementation of the aggregation algorithms (decision trees)

The two developed algorithms were new on the field of SDA. The damage aggregation algorithm was the first on trying to comprehensively aggregate the information obtained from the different available views of the buildings, and the certainty aggregation algorithm added a new dimension in the SDA that allowed to infer conclusions about the reliability of the final damages scores.

The damage aggregation algorithm was developed to summarize damage information, however, it would have to be tuned in order to be applied for different end-users requirements, such as safety assessments or economic loss assessments. Besides the aggregation of the information, the algorithm was also meant to overcome the already mentioned issue with the underestimation of the damage and the remote sensing techniques (CAR, 2013). This was one of the reason to give such an importance to the D4 elements, however, the main reason was that it was understood that in case of presence of one D4 element, it could affect to the whole structure of the building which would made the entire building a D4. The rest of the damage levels (D1-D3) were applied symmetrically through the algorithm since their presence do not have such a severe implication on the structure as the D4 and, thus, they do not affect the other parts of the buildings It is important to notice that, all these were assumptions made for this study, more discussion should be done on this to develop an aggregation algorithm that would capture the reasoning and thinking of the SDA experts on the ground when they use the EMS-98 to classify the affected buildings.

The approach for the aggregation of the certainty measurements was easier, it only had to aggregate the certainty measurement to provide a hint in the reliability of the final damage score produced, so it does not need further discussion. However, a decision that was taken and that had to do with the aggregation of the certainty measurements was that the value of the certainty measurement did not have and an effect on the value of the per-building damage score. This implied that even if a building was classified as D4 but the aggregated certainty value for the whole classification was very low, the final D4 score would not change.

5.4.3. Algorithms test

The purpose of this test was to prove that the algorithms could work properly in a real scenario, where there would be hundreds of damage scores to aggregate.

In the results was already shown that this two algorithms performed well in a simulation with 100 sets of damage scores and certainty measurements. For the aggregation of the simulated damage scores the effect of the high importance given to the D4 façades, in combination with the issue already mentioned about the probabilities of having a D4 within the 4 façades per-building, triggered the effect seen in Figure 45 where most of the buildings were classified as D4 and only a few as D3 and D2. Such a strong effect would not

be observed with a real big set of damage scores, because the distribution of the D4 scores would not be random, but the effect of the weight given to the D4 scores would be there and it would reduce the underestimating effect of the remote sensing techniques.
A more important conclusion could be retrieved from the aggregation of the real expert's outcome presented in the Table 12. There, it could be seen that, even though all the experts received the exact same interface with the exact same imagery, the SDA still has that strong subjectivity factor that made the experts aggregated final score go from D1 to D3. This subjectivity factor was even more obvious in the Table 8 were the experts classified each of the façades and roofs with very different damage scores.
It is important to notice that when the fully automatic approach was applied to the interface exercise at the end of the previous section (5.3), the final result was D2, which would have coincided with the average final aggregated expert damage score: D2 (Table 12). This would mean that the proposed translation code in between the damage features and the EMS-98 scale (Table 13) would provide with realistic final damage scores.

5.5. General discusion of the results

In a nutshell, all the discussion points presented above can be summarize as follows:

- **3D point-cloud assessment.** Allowed to spot the buildings that would be classified as D4 or D5 and it passed the buildings that needed a deeper and more detailed SDA based on the OOA damage feature extraction. However, this section had to be more studied in order to make it more automatic
- **OOA damaged features extraction.** Proved that OOA was able to extract the damage features that were reliable for a complete SDA and it performed according to the expectations in a number of different scenarios.
- **The interface.** It was able to present the information to the experts and it set the basis for an environment where to carry out comprehensive SDAs. However, the interface would have to be improved and enhanced in order to incorporate the expert's comments.
- **The aggregation of the multi-view information.** The algorithms created in order to aggregate the per-view damage and certainty information seemed to performance according to their expectations. More research and more sophisticated algorithms should be developed in order to adequate their behaviours to the process that the surveyors follow on-the-field.

6. CONCLUSION AND RECOMMENDATIONS

6.1. Conclusion

This study had the major objective of developing a new methodology able to produce more reliable and comprehensive damage scores per-building by making use of the imagery that an UAV could provide. The 3D point-cloud assessment was proved to be able to visually point out the necessary evidences that would classify an entire building as D4 or D5. The literature review and the meetings with experts on the structural damage assessment field helped to create a reliable set of basic damage features where to focus the OOA damage extraction. The OOA damaged features extraction, with its three rulesets, showed how this state-of-the-art technique was able to deal with very different types of façades and roofs and complete the required extraction of information from the images. The developed interface succeeded in developing an environment where a more comprehensive understanding of the damage in a buildings was possible, although, it would still needed some improvements in order to incorporate all the experts comments and make it more usable. And finally, the algorithms created to aggregate the damage and certainty information were proved to be able to summarize the information obtained from the interface into the per-building level which accomplished the major objective of this research. The answers for the research questions were:

1. **How to organize the information flow?** The information flow, from the raw UAV imagery to the improved per-building damage scores, was organized in the 4 steps described in the methodology: 3D point-cloud assessment, OOA damaged features extraction, interface and aggregation of information.
2. **What are the products that have to be produced from the raw UAV imagery?** Two were the products that had to be produced out of the raw UAV imagery per-building: 3D point-clouds and façade and roofs images.
3. **What are the main damage features that should be extracted by OOA?** After the undertaken literature review the selected damage features were: cracks, holes, interaction of cracks with structural elements and moved tiles.
4. **How to segment the images to highlight the damage features?** The combination of a multiresolution segmentation and a spectral difference segmentation was found as an appropriate segmentation approach to highlight the damage in the façade and roofs
5. **What must be the aim of the OOA rulesets: accurate feature extraction or stand out the damage features in the image?** After the studied done developing the OOA rulesets, the approach followed was more focused on highlighting the damage features, rather than in accurately extract their geometry.
6. **How to create an OOA ruleset that works in more than one scenario?** The top-down approach followed in the classification section of the rulesets and the proper selection of image features was the key point to develop the versatile rulesets.
7. **Which is the best way to present the extracted damage information to the experts?** This study chose to present the information of the damage by using 2D images of the façades and roof. However, according to the experts' feedback, a fully integrated 3D environment would provide better results.
8. **How to integrate the per-view SDA score and the certainty of the classification into a single per-building score?** Two algorithms that tried to simulate the cognitive process followed by the ground-surveyors were developed in order to integrate this information.
9. **How to add a measurement of the certainty in the final damage score?** The approach to add that information for the final damage score was to include a certainty measurement to each of the per-façade/roof classification which were aggregated to the building level by the aggregation algorithm described in the results chapter.
10. **How to test the usability of the interface?** Some experts in the field were contacted in order to ask for their collaboration. These experts went through the interface and completed the exercise which

gave a sense of how they did, besides all the feedback the provided by asking the questions of the questionnaire

11. **How the performance of the two aggregation algorithms can be tested?** A simulated scenario was created in R-studio to simulate the kind of information that the algorithms would have to analyze in a real situation

6.2. Recommendations

The recommendation for future research are:

1. The 3D point-cloud assessment needs some enhancement in order to become a semi- or automatically classification approach where those mentioned D4-D5 evidences could be identified.
2. From the 3D point-clouds and the relative positions of the camera, once the building has been tagged as suitable for the next step of the methodology, the OOA extraction, a technique that automatically identifies the best façade and roof images for the OOA damaged features extraction would be needed.
3. An extra ruleset capable to automatically identify the building type of the image, so that a given image could be directly derived to its appropriate ruleset would help to improve the flow of the methodology.
4. More façade and roof images would be needed in order to develop an even stronger set of rulesets.
5. Investigate about a more proper way to evaluate the semantic accuracy of the OOA damaged feature extractions.
6. More research would be needed in order to develop a method that could integrate as is due the 2D extracted damage features into a 3D point-cloud.
7. The algorithms developed to aggregate the multi-view damage and certainty information would have to be enhanced in order to adequate their performance to more realistic cognitive processes.

LIST OF REFERENCES

Aibotix. (2013). Intelligent autonomous vehicles Retrieved 21/08/2013, 2013, from http://www.aibotix.com/

Altan, O., Toz, G., Kulur, S., Seker, D., Volz, S., Fritsch, D., & Sester, M. (2001). Photogrammetry and geographic information systems for quick assessment, documentation and analysis of earthquakes. *ISPRS Journal of Photogrammetry and Remote Sensing, 55*(5–6), 359-372. doi: http://dx.doi.org/10.1016/S0924-2716(01)00025-9

Applied-Technology-Council. (2005). *ATC 20-1. Field manual: Post-earthquake safety evaluation of buildings* (Vol. Second edition). Redwood city, California: Applied technology council.

ATC. (2005). ATC 20-2 Appendix A: Guidelines for Owners and Occupants of Damaged Buildings Retrieved 5/08/2013, 2013, from https://www.atcouncil.org/pdfs/ATC202appendixA.pdf

Autodesk-123D. (2013). Autodesk-123D Retrieved 19/08/2013, 2013, from http://www.123dapp.com/catch

Baggio, C., Bernardini, A., Colozza, R., Corazza, L., Della-Bella, M., Di-Pasquale, G., Dolce, M., Goretti, A., Martinelli, A., Orsini, G., Papa, F., & Zuccaro, G. (2007). *Field Manual for post-earthquake damage and safety assessment and short term countermeasures (AeDES)*. Italy.

Barrington, L., Ghosh, S., Greene, M., Har-Noy, S., Berger, J., Gill, S., Lin, A. Y. M., & Huyck, C. (2011). Crowdsourcing earthquake damage assessment using remote sensing imagery. *Annals of Geophysics, 54*(6), 680-687. doi: 10.4401/ag-5324

Baumann, P. (2001). History of remote sensing, aerial photography. Retrieved 2/6/2013, 2013, from http://www.oneonta.edu/faculty/baumanpr/geosat2/RS%20History%20I/RS-History-Part-1.htm

Blaschke, T. (2010). Object based image analysis for remote sensing. *ISPRS Journal of Photogrammetry and Remote Sensing, 65*(1), 2-16. doi: http://dx.doi.org/10.1016/j.isprsjprs.2009.06.004

CAR. (2010). Port-au-Prince Earthquake Damage Assessment using Pictometry: Cambridge Architectural Research Ltd.

CAR. (2013). Cambridge Architectural Research Ltd Retrieved 21/08/2013, 2013, from http://www.carltd.com/risk

Chen, P., Liew, S. C., & Kwoh, L. K. (2005, 25-29 July 2005). *Tsunami damage assessment using high resolution satellite imagery: a case study of Aceh, Indonesia.* Paper presented at the Geoscience and Remote Sensing Symposium, 2005. IGARSS '05. Proceedings. 2005 IEEE International.

Corbane, C., Saito, K., Dell'Oro, L., Bjorgo, E., Gill, S. P. D., Piard, B. E., Huyck, C. K., Kemper, T., Lemoine, G., Spence, R. J. S., Shankar, R., Senegas, O., Ghesquiere, F., Lallemant, D., Evans, G. B., Gartley, R. A., Toro, J., Ghosh, S., Svekla, W. D., Adams, B. J., & Eguchi, R. T. (2011). A comprehensive analysis of building damage in the 12 January 2010 MW7 Haiti earthquake using high-resolution satelliteand aerial imagery. *Photogrammetric Engineering and Remote Sensing, 77*(10), 997-1009.

Curtis, A., & Fagan, W. F. (2013). Capturing Damage Assessment with a Spatial Video: An Example of a Building and Street-Scale Analysis of Tornado-Related Mortality in Joplin, Missouri, 2011. *Annals of the Association of American Geographers*, null-null. doi: 10.1080/00045608.2013.784098

Dell'Acqua, F. (2013). [Field visit to the Univeristy of Pavia].

Dell'Acqua, F., & Gamba, P. (2012). Remote Sensing and Earthquake Damage Assessment: Experiences, Limits, and Perspectives. *Proceedings of the IEEE, 100*(10), 2876-2890. doi: 10.1109/jproc.2012.2196404

Dell'Acqua, F., & Polli, D. A. (2011). Post-event only VHR radar satellite data for automated damage assessment: A study on COSMO/SkyMed and the 2010 Haiti earthquake. *Photogrammetric Engineering and Remote Sensing, 77*(10), 1037-1043.

Dong, L., & Shan, J. (2013). A comprehensive review of earthquake-induced building damage detection with remote sensing techniques. *ISPRS Journal of Photogrammetry and Remote Sensing, 84*(0), 85-99. doi: http://dx.doi.org/10.1016/j.isprsjprs.2013.06.011

Drăguţ, L., Tiede, D., & Levick, S. R. (2010). ESP: a tool to estimate scale parameter for multiresolution image segmentation of remotely sensed data. *International Journal of Geographical Information Science, 24*(6), 859-871. doi: 10.1080/13658810903174803

EEFI. (2013). Institution of Structural Engineers: The Earthquake Engineering Field Investigation Team Retrieved 13/11/2013, 2013, from http://www.istructe.org/resources-centre/technical-topic-areas/eefit

Ehrlich, D., Guo, H. D., Molch, K., Ma, J. W., & Pesaresi, M. (2009). Identifying damage caused by the 2008 Wenchuan earthquake from VHR remote sensing data. *International Journal of Digital Earth, 2*(4), 309-326. doi: 10.1080/17538940902767401

ESRI. (2013). ArcGIS Retrieved 18/12/2013, 2013, from http://www.esri.com/software/arcgis

Fadel, I. E. (2013). *Earth structure using integrated satellite gravity, seismic tomography and 3D object oriented analysis.* (Msc), University of Twente Faculty of Geo-Information and Earth Observation (ITC), Enschede.

Gerke, M. (2011). Supervised Classification of Multiple View Images in Object Space for Seismic Damage Assessment. *Photogrammetric Image Analysis, 6952*, 221-232. doi: 10.1007/978-3-642-24393-6_19

Gerke, M., & Kerle, N. (2011a). Automatic Structural Seismic Damage Assessment with Airborne Oblique Pictometry (c) Imagery. *Photogrammetric Engineering and Remote Sensing, 77*(9), 885-898.

Gerke, M., & Kerle, N. (2011b, 6-13 Nov. 2011). *Graph matching in 3D space for structural seismic damage assessment.* Paper presented at the Computer Vision Workshops (ICCV Workshops), 2011 IEEE International Conference on.

Harwin, S., & Lucieer, A. (2012). Assessing the Accuracy of Georeferenced Point Clouds Produced via Multi-View Stereopsis from Unmanned Aerial Vehicle (UAV) Imagery. *Remote Sensing, 4*(6), 1573-1599.

ImageCat. (2011). GEO-CAN Retrieved 19-11-2013, 2013, from https://www.eeri.org/projects/learning-from-earthquakes-lfe/geo-can/

Ince, G. (2011). The relationship between the performance of soil conditions and damage following an earthquake: A case study in Istanbul, Turkey. *Natural Hazards and Earth System Science, 11*(6), 1745-1758. doi: 10.5194/nhess-11-1745-2011

International-Charter. (2013). The internation Charter Retrieved 17/08/2013, 2013, from http://www.disasterscharter.org/

Joshi, J. R. (2010). *Improving the quality of digital surface model generated from very high resolution satellite stereo imagery by using object oriented image analysis technique.* University of Twente Faculty of Geo-Information and Earth Observation (ITC), Enschede. Retrieved from http://www.itc.nl/library/papers_2010/msc/gfm/janak.pdf

Kerle, N. (2010). Satellite-based damage mapping following the 2006 Indonesia earthquake—How accurate was it? *International Journal of Applied Earth Observation and Geoinformation, 12*(6), 466-476. doi: http://dx.doi.org/10.1016/j.jag.2010.07.004

Kerle, N., Heuel, S., & Pfeifer, N. (2008). Real-time data collection and information generation using airborne sensors. *Geospatial Information Technology for Emergency Response*, 43-74.

Kerle, N., & Hoffman, R. R. (2013). Collaborative damage mapping for emergency response: the role of Cognitive Systems Engineering. *Natural Hazards and Earth System Sciences, 13*(1), 97-113. doi: 10.5194/nhess-13-97-2013

Khoshelham, K., Oude Elberink, S., & Sudan, X. (2013). Segment-Based Classification of Damaged Building Roofs in Aerial Laser Scanning Data. *Geoscience and Remote Sensing Letters, IEEE, 10*(5), 1258-1262. doi: 10.1109/lgrs.2013.2257676

Lemoine, G., Corbane, C., Louvrier, C., & Kauffmann, M. (2013). Intercomparison and validation of building damage assessments based on post-Haiti 2010 earthquake imagery using multi-source reference data. *Nat. Hazards Earth Syst. Sci. Discuss., 1*(2), 1445-1486. doi: 10.5194/nhessd-1-1445-2013

Li, P. J., Xu, H. Q., & Guo, J. C. (2010). Urban building damage detection from very high resolution imagery using OCSVM and spatial features. [Article]. *International Journal of Remote Sensing, 31*(13), 3393-3409. doi: 10.1080/01431161003727705

Mitomi, H., Saita, J., Matsuoka, M., & Yamazaki, F. (2001, 2001). *Automated damage detection of buildings from aerial television images of the 2001 Gujarat, India earthquake.* Paper presented at the Geoscience and Remote Sensing Symposium, 2001. IGARSS '01. IEEE 2001 International.

Mormile, M. (2012). UAV image of a facade in Italy.

Morton, D. C., DeFries, R. S., Nagol, J., Souza Jr, C. M., Kasischke, E. S., Hurtt, G. C., & Dubayah, R. (2011). Mapping canopy damage from understory fires in Amazon forests using annual time series of Landsat and MODIS data. *Remote Sensing of Environment, 115*(7), 1706-1720. doi: http://dx.doi.org/10.1016/j.rse.2011.03.002

Mueller, M., Segl, K., Heiden, U., & Kaufmann, H. (2006). Potential of High-Resolution Satellite Data in the Context of Vulnerability of Buildings. *Natural Hazards, 38*(1-2), 247-258. doi: 10.1007/s11069-005-8637-x

Nonami, K., Kendoul, F., Suzuki, S., Wang, W., & Daisuke, N. (2010). *Autonomous flying robots*: Springer Verlag.

Ogawa, N., & Yamazaki, F. (2000). *Photo-interpretation of building damage due to earthquakes using aerial photogrpahs.* Paper presented at the 12WCEE.

Okada, S., & Takai, N. (2000). *Classification of structural types and damage patterns of buildings for earthquake field investigation.* Paper presented at the 12 World Conference on Earthquake Engineering.

Oude Elberink, S. J., Shoko, M., Fathi, S. A. M., & Rutzinger, M. (2011). Detection of collapsed buildings by classifying segmented airborne laser scanner data. *In: ISPRS workshop laser scanning 2011, Calgary, Canada, 29-31 August 2011 / ed. by D.D. Lichti and A.F. Habib. - : International Society for Photogrammetry and Remote Sensing (ISPRS), 2011. - (International Archives of Photogrammetry and Remote Sensing : IAPRS : ISPRS ; XXXVIII-5/W12). 6 p.*

Pesaresi, M., Gerhardinger, A., & Haag, F. (2007). Rapid damage assessment of built-up structures using VHR satellite data in tsunami-affected areas. *International Journal of Remote Sensing, 28*(13-14), 3013-3036. doi: 10.1080/01431160601094492

Pictometry. (2013). Homepage of Pictometry Inc., from http://pictometry.com/

Protezione-Civile. (1998). EMS 98 Retrieved 3/6/2013, 2013, from http://www.protezionecivile.gov.it/cms/attach/editor/rischio-sismico/Scala_EMS-1998.pdf

R. (2012). The R-project for statistical computing Retrieved 18/12/2013, 2013, from http://www.r-project.org/

Rasika, A. K., Kerle, N., & Heuel, S. R. K. B. (2006). Multi - scale texture and color segmentation of oblique airborne video data for damage classification. *In: ISPRS 2006 : ISPRS mid-term symposium 2006 remote sensing : from pixels to processes, 8-11 May 2006, Enschede, the Netherlands. Enschede : ITC, 2006. 8 p.*

Rodarmel, C., Scott, L., Simerlink, D., & Walker, J. (2002). Multisensor fusion over the World Trade Center disaster site. *Optical Engineering, 41*(9), 2120-2128. doi: 10.1117/1.1497984

Rothermel, M., & Wenzel, K. (2013). SURE: Photogrammetric Surface Reconstruction from Imagery Retrieved 13/1/2014, 2014, from http://www.ifp.uni-stuttgart.de/publications/software/sure/index.en.html

Saito, K., & Spence, R. J. S. (2010). *Damage assessment of Port au Prince using Pictometry.* Paper presented at the 8th International Conference on Remote Sensing for Disaster Response, Tokyo Institute of Technology.

Schweier., Markus, M., & Steinle, E. (2004). Simulation of earthquake caused building damages for the development of fast reconnaissance techniques. *Natural Hazards and Earth System Sciences, 4*(2), 285-293.

Shao, Y., Gong, H., Wang, S. A., Zhang, F., & Tian, W. (2009, 20-22 May 2009). *Multi-source SAR remote sensing data for emergency monitoring to Wenchuan Earthquake damage assessment.* Paper presented at the Urban Remote Sensing Event, 2009 Joint.

Shen, Y., Wu, L., & Wang, Z. (2010, 18-20 June 2010). *Identification of inclined buildings from aerial LIDAR Data for disaster management.* Paper presented at the Geoinformatics, 2010 18th International Conference on.

Skybox. (2013). Skybox imaging Retrieved 28/12/2013, 2013, from http://www.skyboximaging.com/

Stanford-University. (2013). Building Assessment Team (BAT) Retrieved 9/08/2013, 2013, from http://www.stanford.edu/dept/EHS/prod/general/erprep/bat.html

Tiede, D., Lang, S., Fureder, P., Holbling, D., Hoffmann, C., & Zell, P. (2011). Automated Damage Indication for Rapid Geospatial Reporting. *Photogrammetric Engineering and Remote Sensing, 77*(9), 933-942.

Tong, X., Hong, Z., Liu, S., Zhang, X., Xie, H., Li, Z., Yang, S., Wang, W., & Bao, F. (2012). Building-damage detection using pre- and post-seismic high-resolution satellite stereo imagery: A case study of the May 2008 Wenchuan earthquake. *ISPRS Journal of Photogrammetry and Remote Sensing, 68*(1), 13-27. doi: 10.1016/j.isprsjprs.2011.12.004

Trimble-eCognition. (2013). eCognition Retrieved 19/8/2013, 2013, from http://www.ecognition.com/

Trimble. (2011). *eCognition 8.7 reference book.* München, Germany: Trimble Germany.

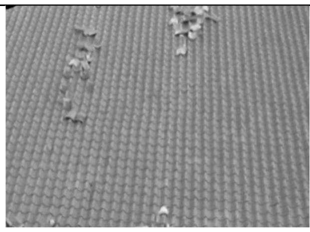
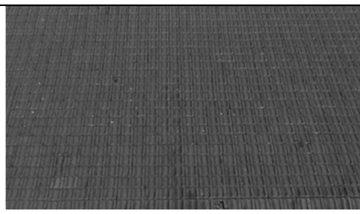
Trimble. (2012). Trimble eCognition Retrieved 18/12/2013, 2013, from http://www.trimble.com/

UNITAR. (2013). United Nations Institute for Training and Research: Operational Satellite Applications Programme, from http://www.unitar.org/unosat/

Weindorf, M., Vögtle, T., & Bähr, H. P. (1999). An approach for the detection of damages in buildings from digital aerial information. In F. Wenzel, D. Lungu & O. Novak (Eds.), *Vrancea Earthquakes: Tectonics, Hazard and Risk Mitigation* (Vol. 11, pp. 341-348): Springer Netherlands.
Wen, Q., Chen, S., He, H., Li, S., Bai, R., & Zhao, X. (2012). Application of remote sensing system of unmanned aerial vehicle in Yingjiang, Yunnan earthquake. *Journal of Natural Disasters, 21*(6), 65-71.
Xiao, J., Gerke, M., & Vosselman, G. (2012). Building extraction from oblique airborne imagery based on robust façade detection. *ISPRS Journal of Photogrammetry and Remote Sensing, 68*(0), 56-68. doi: http://dx.doi.org/10.1016/j.isprsjprs.2011.12.006
Yamazaki, F., & Matsuoka, M. (2007). Remote sensing technologies in post-disaster damage assessment. *Journal of Earthquake and Tsunami, 01*(03), 193-210. doi: doi:10.1142/S1793431107000122
Yamazaki, F., Suzuki, D., & Maruyama, Y. (2008). *Detection of Damages due to Earthquakes using Digital Aerial Images*. Paper presented at the 6th International Workshop on Remote Sensing for Disaster Applications, Pavia, Italy.

7. APPENDIX

7.1. Images inventory

<table>
<tr><td>Concrete façade 1</td><td>Brick façade 3</td></tr>
<tr><td></td><td></td></tr>
<tr><td>Concrete façade 2</td><td>Roof 1</td></tr>
<tr><td></td><td></td></tr>
<tr><td>Concrete façade 3</td><td>Roof 2</td></tr>
<tr><td>
</td><td></td></tr>
<tr><td>Concrete façade 4</td><td>Concrete façade 1 edited</td></tr>
<tr><td></td><td></td></tr>
<tr><td>Brick façade 1</td><td>Concrete façade 2 edited</td></tr>
<tr><td></td><td></td></tr>
<tr><td>Brick façade 2</td><td>Concrete façade 4 edited</td></tr>
</table>

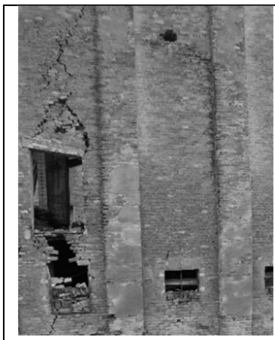
	

Table 15. Inventory of the images used in this study

7.2. 3D models inventory

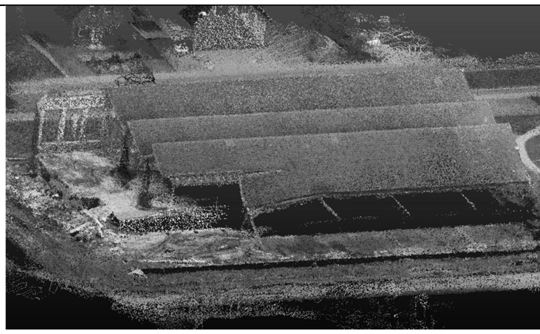
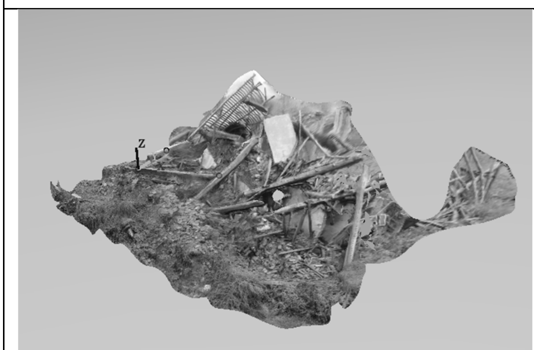
Italian house 1	**Italian house 4**
	
Italian house 2	**Gronau's factory**
	
Italian house 3	
	

Table 16. Inventory of the 3D models used in this study

7.3. Classification results inventory

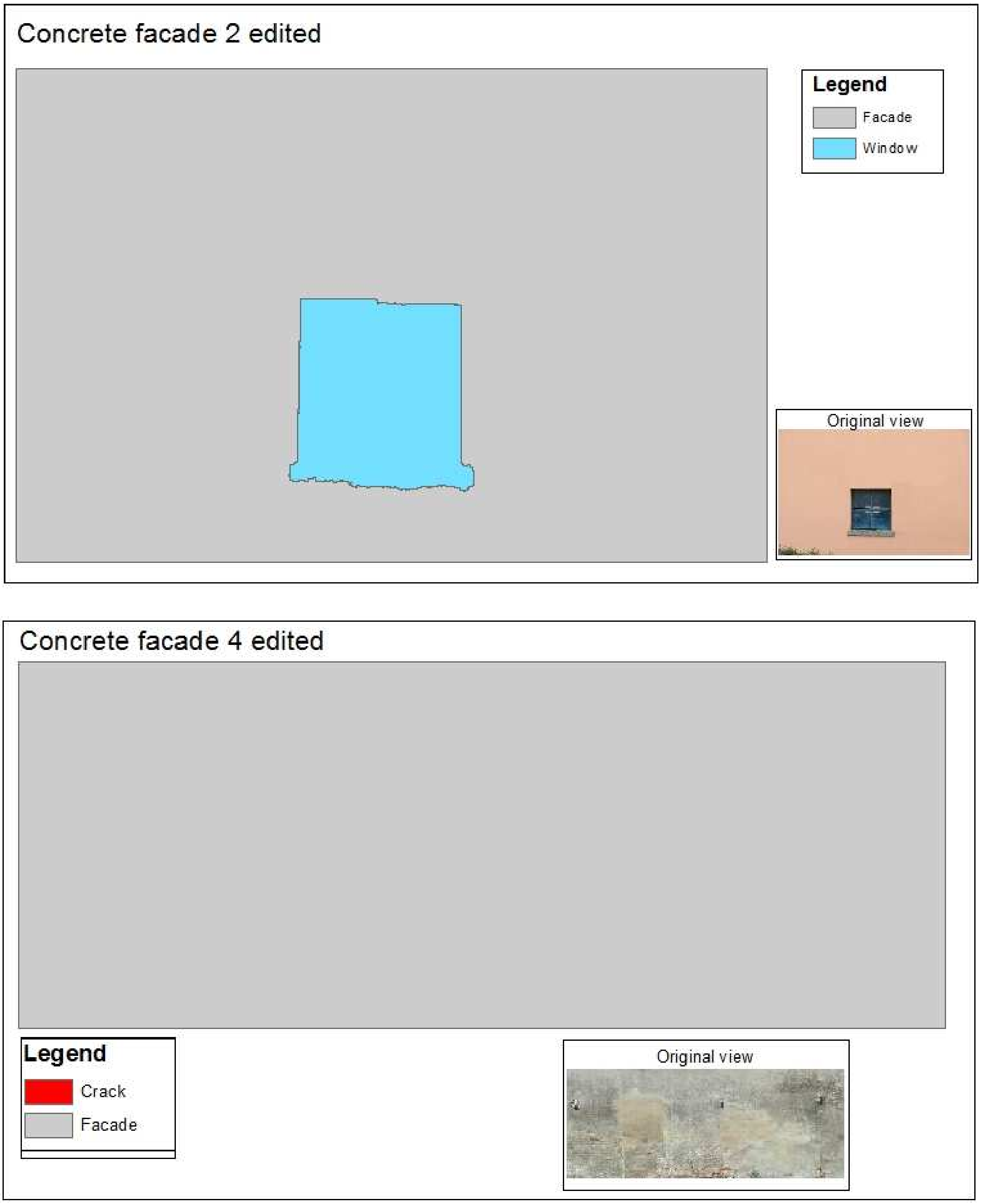


Figure 54. Classification results of the application of the concrete façade ruleset (concrete façade 2 & 4 edited)

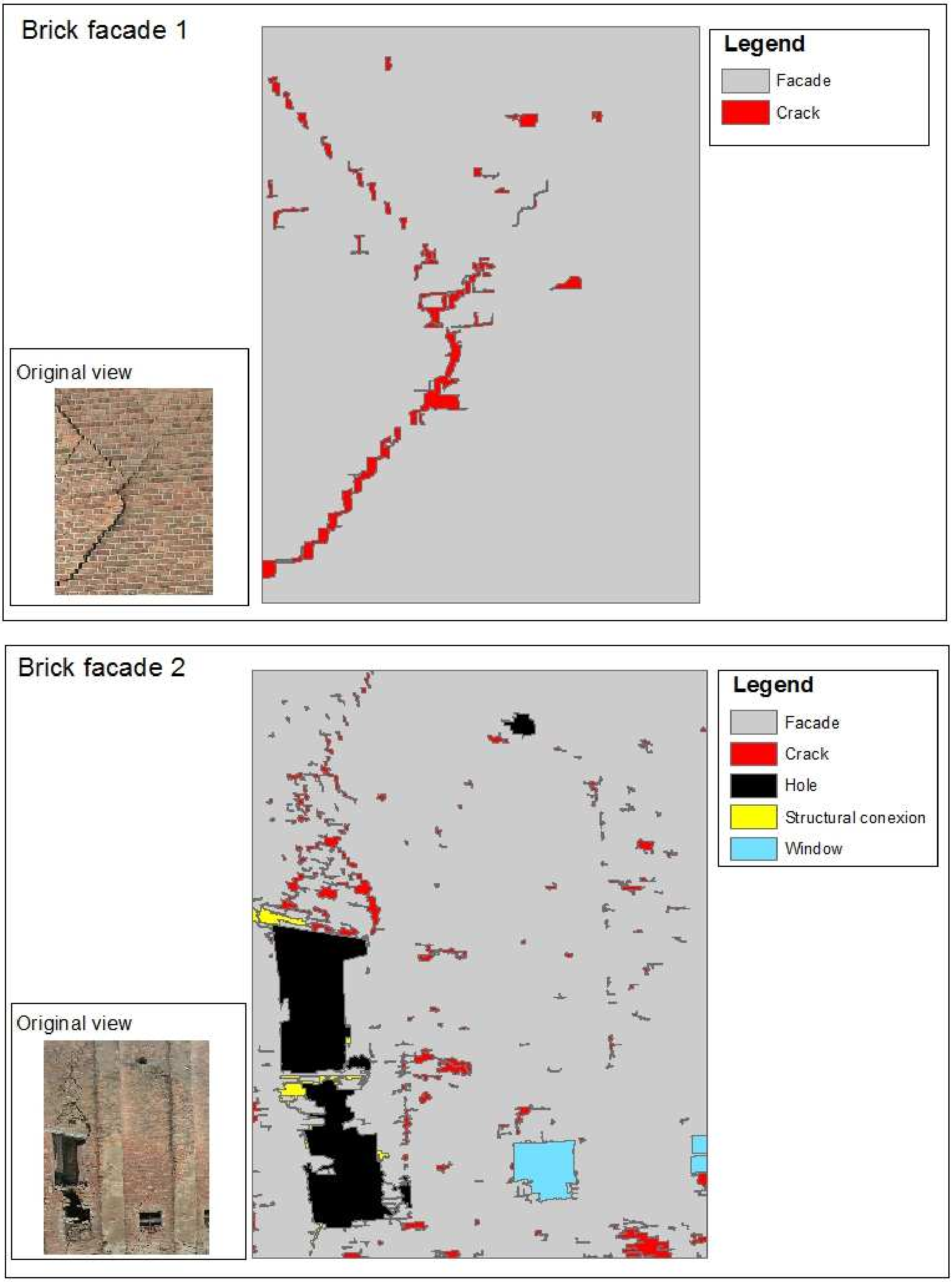


Figure 55. Classification results of the application of the brick façade ruleset (Brick façades 1 & 2)

7.4. Rulesets code

CONCRETE FAÇADE RULSET

Classes:

```
Column
crack
Façade
structural crossing
structural_connexion
window
```

Process: Main:

```
fast_run
    segmentation
        multiresolution segmentation: 100 [shape:0.8 compct.:0.5] creating 'New Level'
        spectral difference segmentation: at  New Level: spectral difference 20
    classification
        windows
            assign class: with Max. diff. <= 0.36  at  New Level: window
            if: window at  New Level: if Area >= 2000000 Pxl
                then: then
                    assign class: window at  New Level: Façade
                else: else
                    assign class: window at  New Level: window
            merge region: window at  New Level: merge region
        Structural_elements
            if: if Length\Width >= 1.2
                assign class: window with Length\Width >= 1.2  at  New Level: Column
        façade
            if: if Rel. border to window >= 1
                assign class: Façade with Rel. border to window >= 1  at  New Level: window
            assign class: unclassified at  New Level: Façade
            assign class: Façade with Rel. border to window >= 0.9  at  New Level: window
            merge region: window at  New Level: merge region
    crack_extraction
        potential_cracks
            assign class: Façade with Compactness >= 3  at  New Level: crack
        Crack_refinement
            if: crack at  New Level: if Rel. border to window >= 0.4
                assign class: crack with Rel. border to window >= 0.3  at  New Level: Façade
            multiresolution segmentation: crack at  New Level: 50 [shape:0.5 compct.:0.5]
            if: crack at  New Level: if Rel. border to window >= 0.4
                assign class: crack with Rel. border to window >= 0.3  at  New Level: Façade
            merge region: crack at  New Level: merge region
    semantics
        crossing
            chessboard segmentation: crack at  New Level: chess board: 40
            assign class: crack with Rel. border to Column >= 0.5  at  New Level: structural crossing
```

merge region: structural crossing at New Level: merge region
touching
windows
assign class: crack with Rel. border to window >= 0.001 at New Level: structural_touching
columns
assign class: crack with Rel. border to Column > 0 at New Level: structural_touching
aggregation
merge region: Column at New Level: merge region
merge region: crack at New Level: merge region
merge region: structural crossing at New Level: merge region
merge region: structural_touching at New Level: merge region
merge region: Façade at New Level: merge region
merge region: window at New Level: merge region

BRICK FAÇADE RULSET

Classes:

Column
crack
damage
Façade
hole
structural crossing
structural_connexion
window

Process: Main:

fast_run
segmentation
multiresolution segmentation: 25 [shape:0.2 compct.:0.2] creating 'New Level'
spectral difference segmentation: at New Level: spectral difference 35
binary_class
assign class: with Area >= 300000 Pxl at New Level: Façade
assign class: unclassified at New Level: damage
damage_refinement
multiresolution segmentation: refinement of the damage feature
assign class: damage with Rectangular Fit >= 0.87 and Area <= 4500 Pxl at New Level: Façade
assign class: damage with Max. diff. >= 0.33 and Max. diff. <= 0.35 at New Level: Façade
Features_classification
assign class: damage with Area >= 4500 Pxl and Asymmetry <= 0.61 at New Level: hole
assign class: damage at New Level: crack
merge region: Façade, unclassified at New Level: merge region
merge region: crack at New Level: merge region
merge region: hole at New Level: merge region
assign class: hole with Rectangular Fit >= 0.85 and Area <= 100000 Pxl at New Level: window
cracks_refinement
assign class: crack with Length\Width >= 5.6 at New Level: Façade
assign class: crack with Area <= 153 Pxl at New Level: Façade

semantics
touching
windows
assign class: crack with Rel. border to window >= 0.001 at New Level: structural_touching
holes
assign class: crack with Rel. border to hole > 0 at New Level: structural_touching
aggregation
merge region: Column at New Level: merge region
merge region: crack at New Level: merge region
merge region: structural crossing at New Level: merge region
merge region: structural_touching at New Level: merge region
merge region: Façade at New Level: merge region
merge region: window at New Level: merge region
export vector layers: at New Level: export object shapes to ObjectShapes

ROOF RULESET

Classes:
damaged
Intact

Process: Main:
fast_run
classification
assign class: with Area <= 100000 Pxl at New Level: damaged
assign class: unclassified at New Level: Intact
export vector layers: at New Level: export object shapes to ObjectShapes
segmentation
multiresolution segmentation: 75 [shape:0.2 compct.:0.2] creating 'New Level'
spectral difference segmentation: at New Level: spectral difference 25

7.5. Accuracy assessment inventory

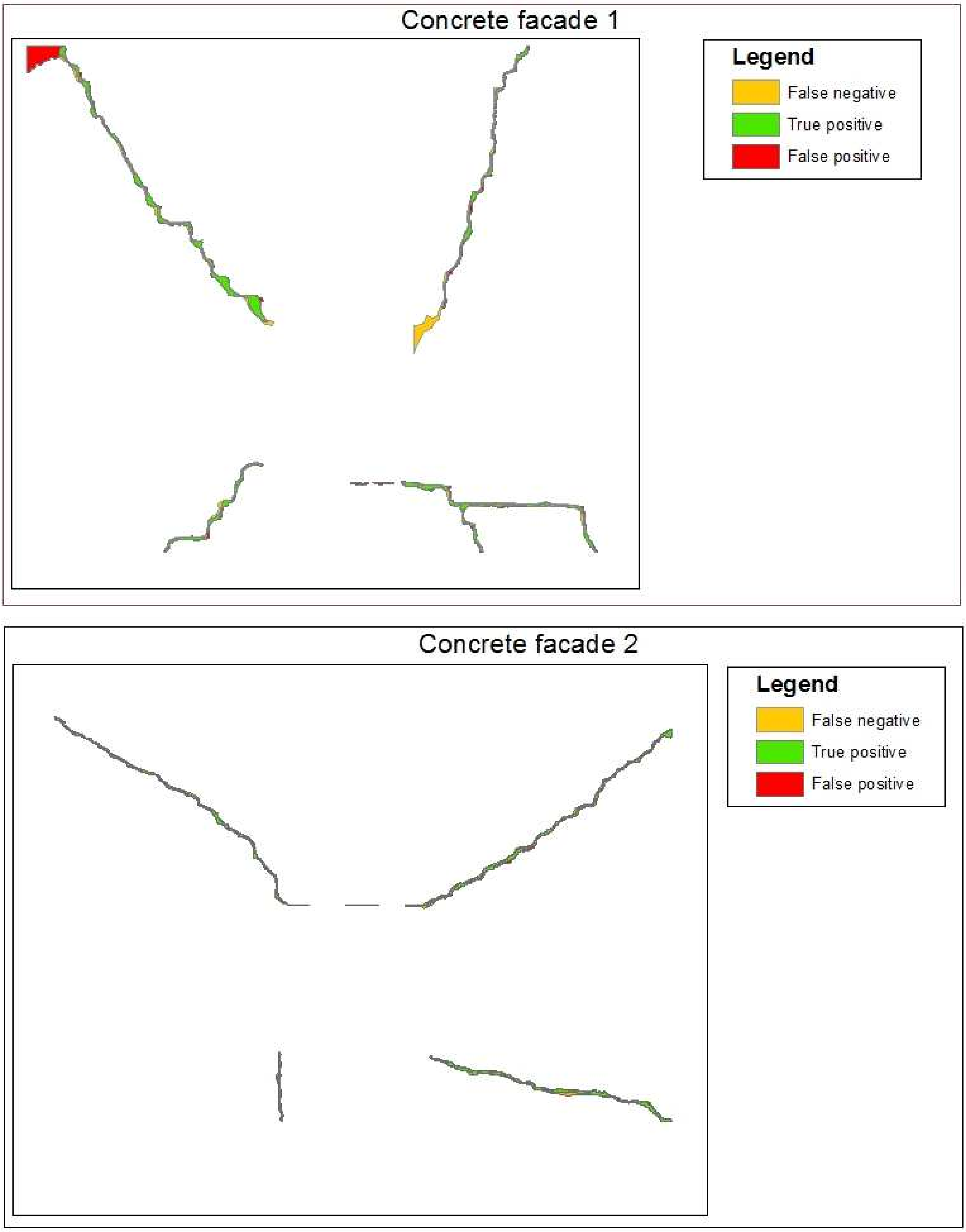
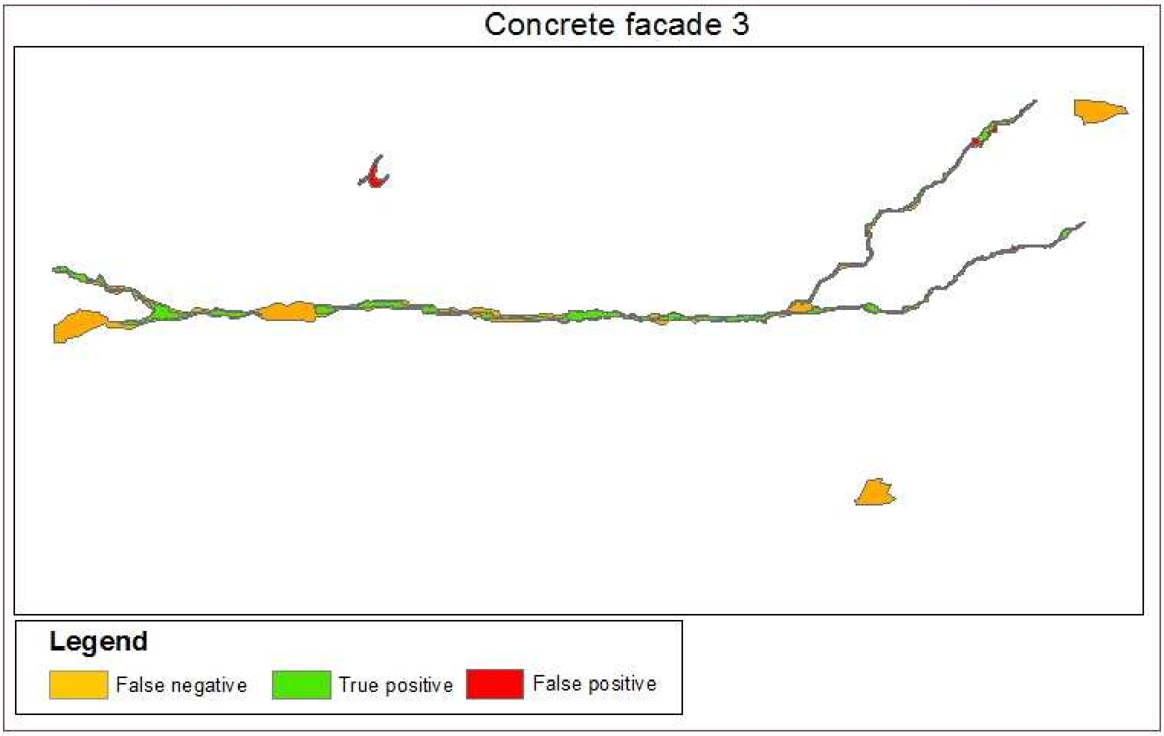


Figure 56. Illustration of the results of the accuracy assessment (Concrete façade 1 & 2)



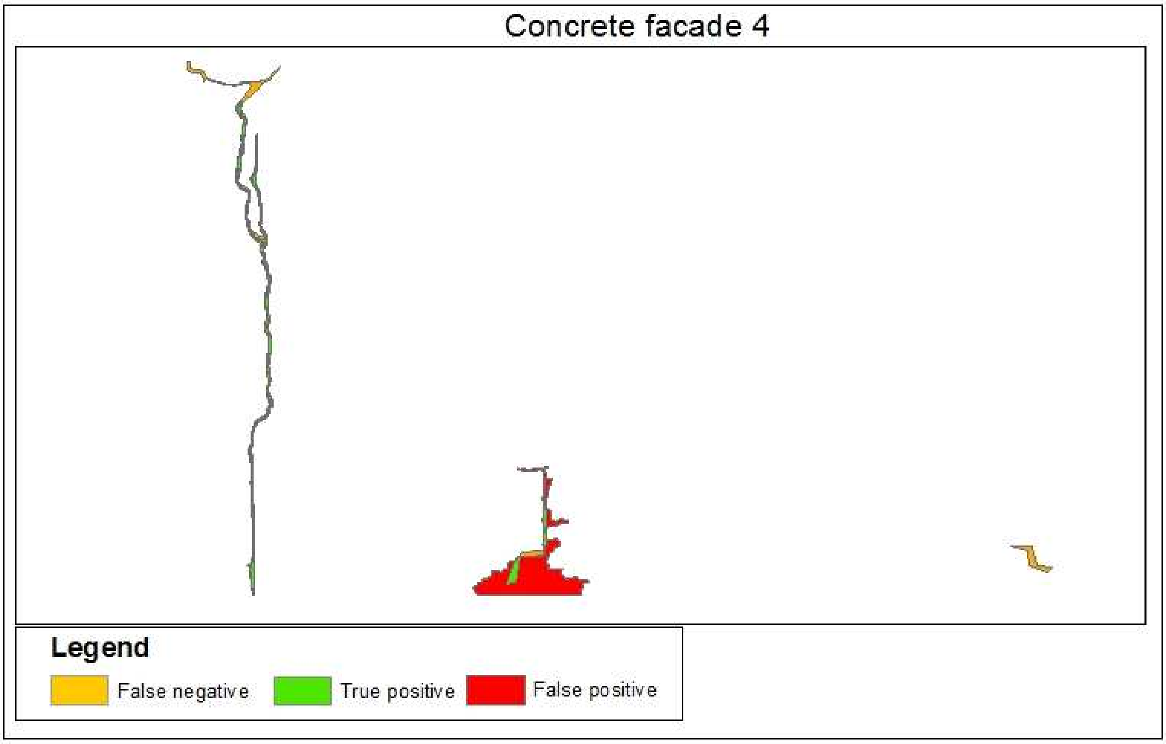


Figure 57. Illustration of the results of the accuracy assessment (Concrete façade 3 & 4)

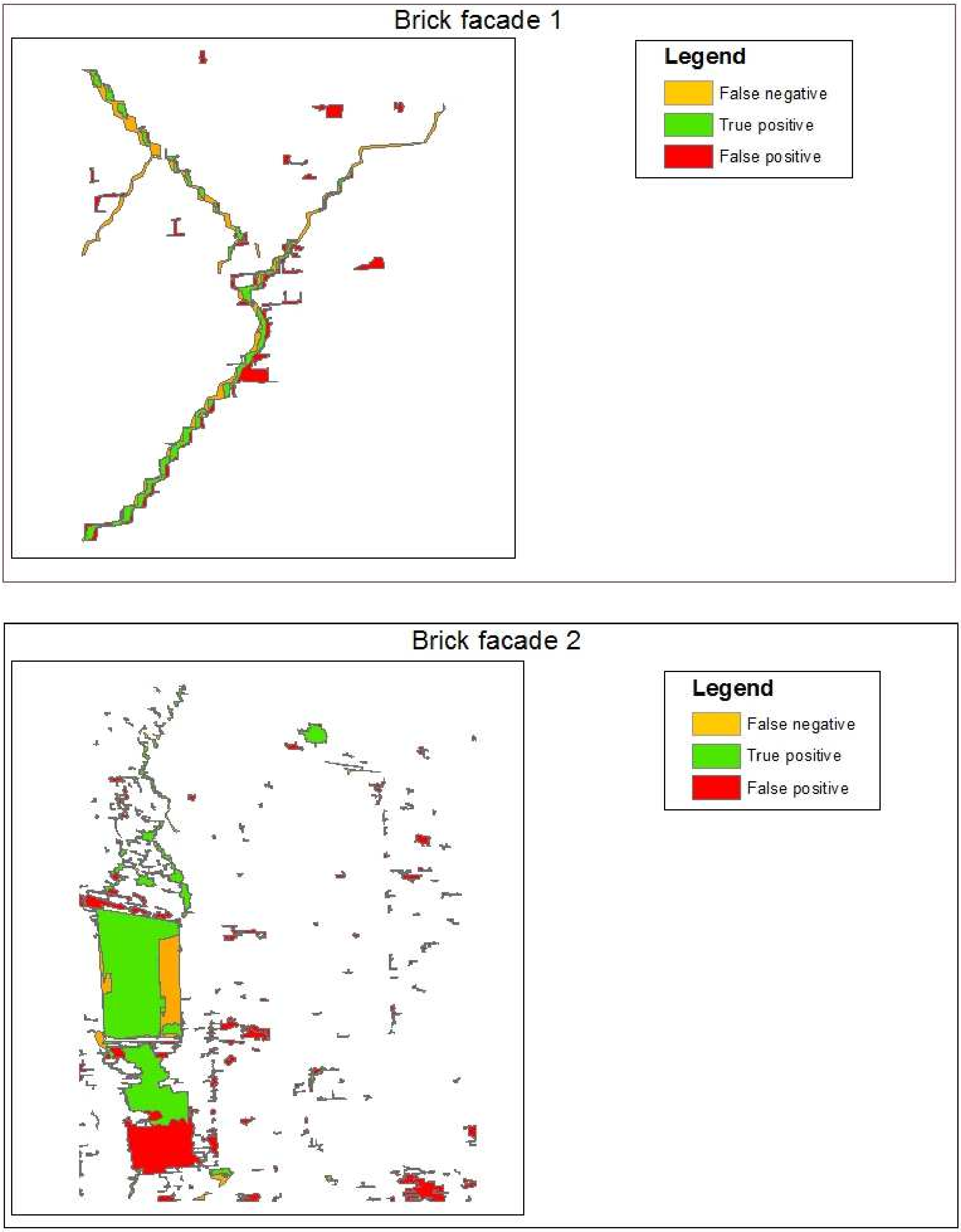


Figure 59. Illustration of the results of the accuracy assessment (brick façades 1 & 2)

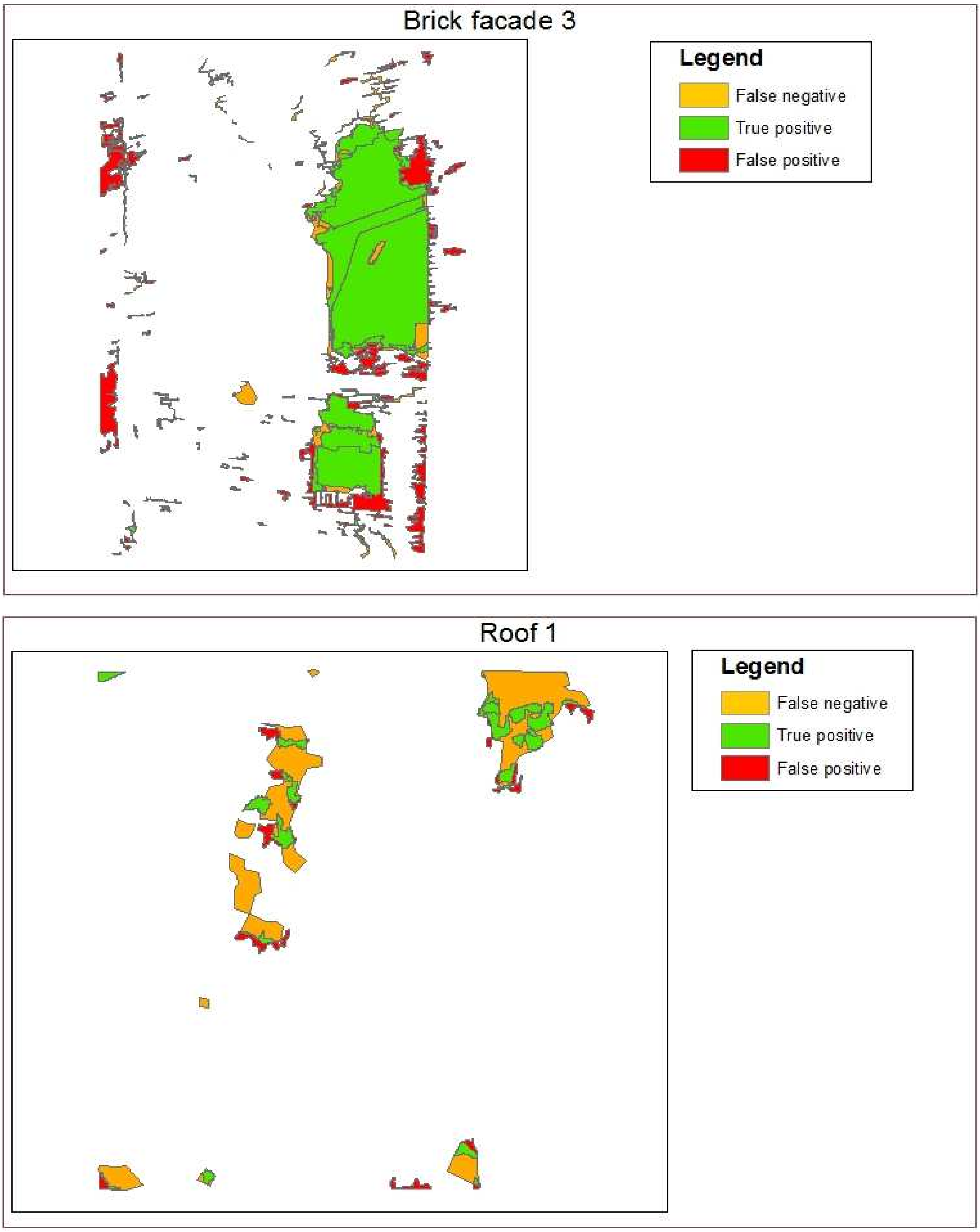


Figure 60. Illustration of the results of the accuracy assessment (brick façade 3 and roof 1)

7.6. Interface's PowerPoint

Structural damage assessment

The bridge between classic remote sensing and the ground-based surveys-

This is an example of how the information extracted from our image analysis process is presented the experts.

The principal aim of this concept prototype is to test its usability. You must know that due time constrains, this prototype has been done in a non-very appropriate environment. In the future, this environment is going to be changed.

At the end of this exercise, you will have to answer a few questions where you can tell us What would you change?, How you would improve this tool?, etc.

This simulation tries to simulate a real case scenario, however, due to data constrains, the 3D model that is presented here doesn't match with the data that has been analyzed.

Explanation of the exercise.

Note: We already assume that you are familiar with the terms that are going to be used in the coming slides.

The purpose of this exercise is to proceed with a per-facade / per-roof structural damage assessment.

A set of images are going to be presented and you are going to be able to use the original images + some EXTRA information. This extra information has been generated by an image analysis technique called **Object-oriented Analysis** or **Object-based Image Analysis** (OOA or OBIA).

By the end of the exercise you are going to generate a set of damage scores. These damage scores will be aggregated into a per-building damage score that takes into account the different realities of a damaged building + includes measurement of the certainty of you classification.

The objective of this study is to develop a technique that creates more comprehensive damage scores by making use of the multi-view UAV imagery available nowadays. We assume that these damage scores are more comprehensive because we all the perspectives of the building are analyzed.

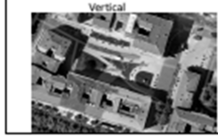
Note. The information analyzed in this process have already went trhough a 3D point cloud assessment where: collapsed buildings, collapsed walls & roofs and severely inclined wall have been detected and classified.

The reasoning behind this study.

Four are the milestones that lead to this study:

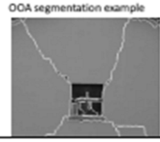
1. Vertical imagery only provides information from the roofs ---> A complete structural damage assessment (SDA) cannot be done because the information from the facades is missing.
2. Oblique imagery stands as a solution to this problems because the facades are visible ---> Most of the times a single image is used to classify the building, the damage observed in one facade are extrapolated to the entire building, which assumes a high uncertainty.
3. The complexity of the damage presented on the building limits the automatic approaches that try to identify the damage features ---> OOA has been proved as a technique that has been able to cope with the complexity of the situation and has extracted the specified damage features from the images.
4. Some oblique studies have tried to integrate the multi-perspective assessment **--->** Their approach is rather manual.

Vertical



Oblique

OOA segmentation example



A few notes before start.

Your evaluation of the images must be done on the DAMAGE basis. This is a structural DAMAGE assessment study, NOT A SAFETY assessment, so although the elements of focus remain the same, their meaning is slightly different.

Each one of the facades or roofs has to be classified regarding to the EMS-98 scale.

	**Grade 4: Very heavy damage (heavy structural damage, very heavy non-structural damage)** Serious failure of walls; partial structural failure of roofs and floors.

Now, you have some time to refresh your knowledge about this scale.

You might miss the level D5, it's not here because our method makes sure that the collapsed building are identified beforehand, in a 3D pointcloud assessment

Classification of damage to masonry buildings	
	**Grade 1: Negligible to slight damage (no structural damage, slight non-structural damage)** Hair-line cracks in very few walls. Fall of small pieces of plaster only. Fall of loose stones from upper parts of buildings in very few cases.
	**Grade 2: Moderate damage (slight structural damage, moderate non-structural damage)** Cracks in many walls. Fall of fairly large pieces of plaster. Partial collapse of chimneys.
	**Grade 3: Substantial to heavy damage (moderate structural damage, heavy non-structural damage)** Large and extensive cracks in most walls. Roof tiles detach. Chimneys fracture at the roof line; failure of individual non-structural elements (partitions, gable walls).
	**Grade 4: Very heavy damage (heavy structural damage, very heavy non-structural damage)** Serious failure of walls; partial structural failure of roofs and floors.

How does the interface work?

This presentation has been made in a way that looks like an interactive interface.

- Like any other presentation, to go from slide to slide you have to use the arrows in your keyboard.
- In the slides with the "interactive sign"(Interactive!) you can use the mouse to click in the images or boxes to access to extra information within the same slide
- There a some steps where you have to add some information: Add building type Tag the view . When click in, an attached *.txt file will pop out. You have to fill in the information for each image; and don't forget, save and close it EACH TIME you have added something, otherwise the changes won't be stored
- Each interactive slide has a number which is related to the part of the txt file that you have to fill in.
- Recommendation, when you open the txt file, make it as wide as your screen, otherwise, due to change on the screen side the structure of the text could be messed up.

If power-point is not in presentation mode yet, you must do it now, otherwise the interface will not work.

START

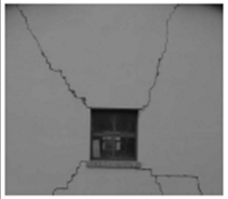
Description

Interactive!

Add building type

[5]

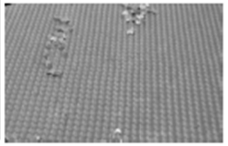
View 1



View 2

View 3

View 4



View 5

3D model simulation

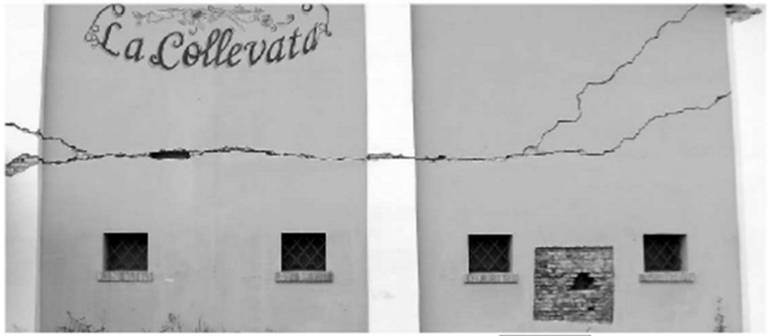
Warning, the following 3D model is just an illustration, it doesn't fit with the data presented in the following slides

Structural damage assessment. VIEW 1

Interactive!

Original view	Classified image	Cracks	Structural crossings

Back to end

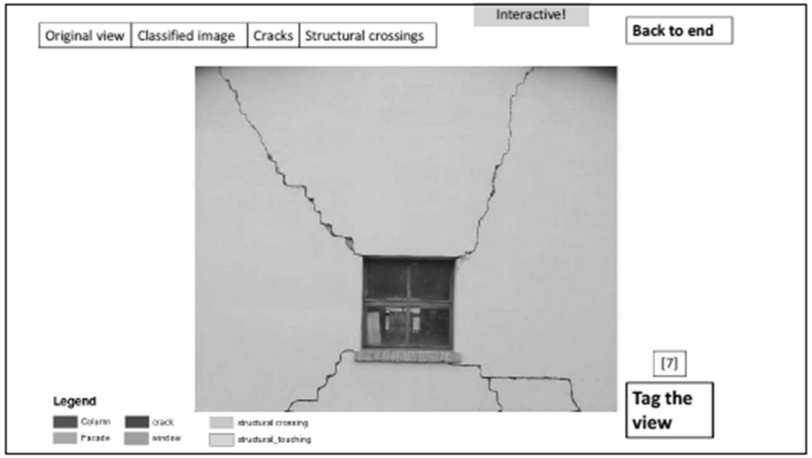


Column Facade crack window structural crossing structural_touching

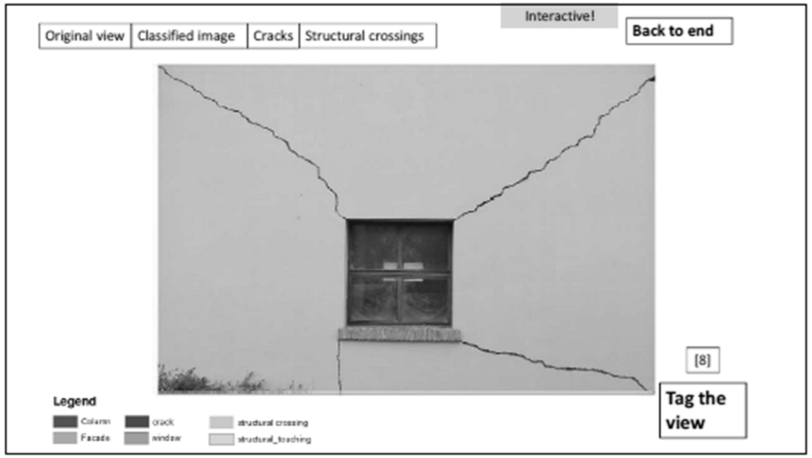
[6]

Tag the view

Structural damage assessment. VIEW 2

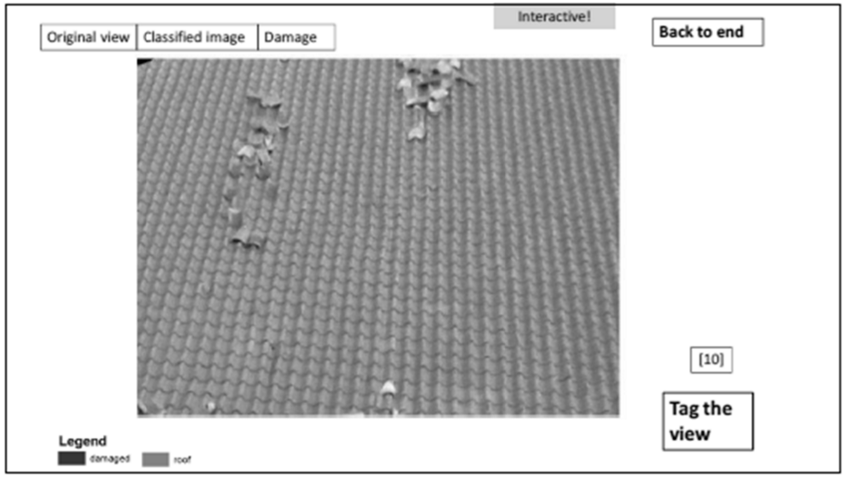


Structural damage assessment. VIEW 3



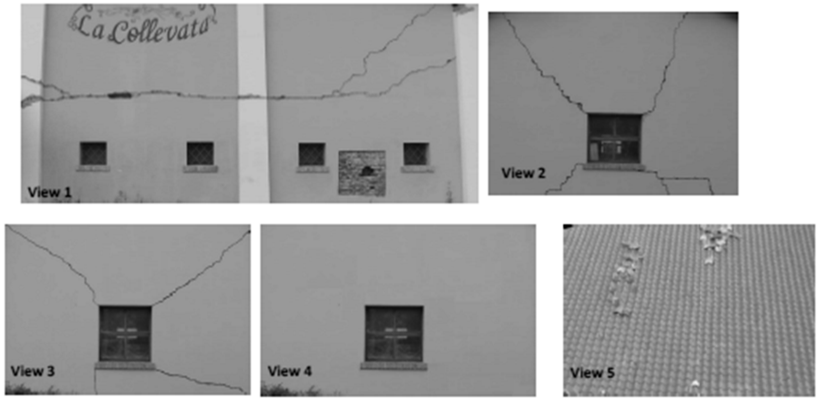
Structural damage assessment. **VIEW 4**

Structural damage assessment. **VIEW 5**



Interactive!

Do you need to go back? Just click on the image you want to go



Example of the integration of the extracted 2D information into the 3D models

Interactive!

The exercise has finished.

Click there to answer to a few questions about your experience with the "interface"

Txt file

Thank you very much for your collaboration, all your comments and suggestions will be taken into account to improve the usability of this interface.

7.7. R-Studio code

```
#Creating the datasets(it is a simulation of 1 expert classifying 100 buildings)

#dataset for damage scores
damage_scores <- data.frame(façade1=c(sample(1:4,100, replace=TRUE)), façade2=c(sample(1:4,100,
replace=TRUE)), façade3=c(sample(1:4,100, replace=TRUE)), façade4=c(sample(1:4,100,
replace=TRUE)),roof=c(sample(1:3,100, replace=TRUE)))
dam = damage_scores
head(dam)

#aggregation of the damage scores
dam.agg = rep(-1, 100)
for(i in 1:100){
  dam_agg_100=(if(4 %in% dam[i,]) dam_agg_100=4 else (if(rowSums(dam[i,]==3)>=3) dam_agg_100=3 else
(if(rowSums(dam[i,]==3)<3 && rowSums(dam[7,]==3)>=1) dam_agg_100=2 else (if(rowSums(dam[i,]==2)>=3)
dam_agg_100=2 else (if(rowSums(dam[i,]==2)<3) dam_agg_100=1 else dam.agg=1)))))
  dam.agg[i] = dam_agg_100
}
plot(dam.agg)
as.data.frame(dam.agg)

#Dataset for certainty measurements
certainty_scores <- data.frame(façade1=c(sample(1:3,100, replace=TRUE)), façade2=c(sample(1:3,100,
replace=TRUE)), façade3=c(sample(1:3,100, replace=TRUE)), façade4=c(sample(1:3,100,
replace=TRUE)),roof=c(sample(1:3,100, replace=TRUE)))
cer=certainty_scores
head(cer)

#aggregation of the information for the certainty measurements
cer_agg_test=(sum(cer[21,])*100/15)

cer.agg = rep(1, 100)
for(i in 1:100){
  cer_agg_100=(sum(cer[i,])*100/15)
  cer.agg[i] = cer_agg_100
}
plot(cer.agg)
cer.agg
as.data.frame(cer.agg)
```

Simulated damage scores						Simulated certainty measurements				
House	**façade1**	**façade2**	**façade3**	**façade4**	**roof**	**façade1**	**façade2**	**façade3**	**façade4**	**roof**
1	4	3	2	3	2	1	3	3	1	1
2	4	1	4	4	1	3	3	3	2	2
3	1	2	2	1	1	2	2	3	2	1
4	2	3	3	3	3	1	3	3	1	1
5	2	2	4	4	3	1	3	1	1	1
6	2	2	3	1	3	3	2	1	2	2
7	3	4	3	4	2	3	1	1	1	3
8	1	3	3	2	2	2	3	3	3	3
9	4	2	3	3	2	3	2	2	3	3
10	2	4	2	3	1	1	2	2	3	3
11	2	3	1	4	3	2	2	3	3	3
12	4	2	1	4	3	2	1	3	3	3
13	1	3	4	1	3	1	3	1	3	1
14	1	2	4	3	3	2	1	1	1	1
15	2	3	2	2	2	1	2	1	1	2
16	4	2	3	1	3	1	2	2	1	3
17	1	3	2	1	2	3	1	2	3	2
18	1	4	3	3	2	2	1	2	2	1
19	3	1	1	4	1	3	2	1	2	3
20	4	3	1	2	3	2	2	2	2	2
21	2	1	3	3	3	2	2	2	2	3
22	2	1	1	4	1	1	3	3	1	2
23	1	3	4	4	1	2	1	2	1	1
24	2	4	3	1	2	2	1	2	3	3
25	4	2	2	3	3	3	2	2	2	3
26	3	3	1	2	1	1	2	3	1	1
27	4	2	1	2	3	3	2	1	2	3
28	3	1	4	1	3	3	1	2	3	3
29	1	4	2	3	3	1	3	2	3	2
30	3	4	2	3	2	3	3	1	1	1
31	4	1	2	2	1	1	1	3	1	1
32	2	2	1	3	2	3	2	1	1	3
33	3	3	4	2	1	2	1	2	1	2
34	4	2	2	4	2	3	2	1	1	1
35	4	2	2	1	1	2	1	3	2	2
36	1	4	2	3	3	1	2	2	2	2
37	1	4	3	2	3	2	3	3	2	3
38	1	1	4	1	2	2	1	3	3	2
39	3	1	3	2	1	3	2	1	3	2
40	2	2	4	1	2	3	3	3	1	1
41	2	1	3	3	1	2	3	3	3	3
42	2	3	4	2	1	1	1	3	1	1
43	2	3	3	4	2	3	1	1	3	2
44	4	1	1	2	3	2	3	3	3	2
45	2	1	4	1	3	2	1	1	2	1
46	3	4	3	4	1	2	2	2	2	1
47	3	4	4	1	1	3	2	1	3	3
48	2	4	1	4	3	1	1	1	2	1
49	2	4	4	2	3	2	3	2	1	3
50	2	2	2	1	1	1	1	1	3	1
51	1	1	3	4	3	2	3	3	1	1
52	2	2	4	3	1	3	1	3	1	3
53	4	2	4	4	3	1	1	2	1	1
54	1	4	1	3	1	2	2	3	2	2
55	2	2	2	2	1	2	1	2	3	3

56	4	2	4	4	3	2	3	3	1	2
57	2	3	1	2	3	2	2	3	1	2
58	1	1	2	4	1	1	1	3	3	1
59	2	2	1	4	1	3	1	3	3	1
60	3	4	4	2	2	3	1	2	2	2
61	4	3	3	2	3	3	3	1	2	1
62	1	1	4	4	3	3	2	3	1	1
63	1	4	1	3	2	2	1	1	2	3
64	1	2	2	2	1	1	2	2	1	3
65	2	2	3	3	1	3	2	3	1	3
66	3	3	4	3	1	2	2	3	1	3
67	3	2	1	3	3	1	1	1	3	1
68	3	3	4	1	1	1	3	2	1	3
69	3	3	1	1	1	3	2	3	3	3
70	4	4	2	4	2	1	2	3	1	3
71	3	3	4	4	1	2	1	2	2	3
72	1	2	2	3	1	1	3	2	1	3
73	3	4	3	1	3	1	1	1	3	2
74	4	4	4	3	3	2	1	3	2	2
75	4	1	1	1	1	3	3	2	3	2
76	2	2	1	4	1	2	1	3	2	3
77	1	4	4	2	2	1	2	2	1	3
78	4	4	3	2	3	2	3	2	1	1
79	3	4	1	3	3	1	3	1	3	1
80	4	3	1	1	1	3	2	3	1	1
81	4	4	3	2	1	3	1	1	1	2
82	2	1	1	1	3	1	3	1	1	3
83	4	4	3	4	2	3	3	2	1	3
84	1	2	3	3	2	2	2	2	2	1
85	1	3	3	2	2	3	1	2	1	3
86	1	4	3	4	3	1	3	3	1	2
87	2	4	2	1	2	3	2	1	3	1
88	4	1	2	2	3	2	1	2	3	3
89	3	2	2	1	2	2	2	2	1	1
90	2	2	2	1	2	2	3	1	3	3
91	3	1	1	4	1	3	1	1	2	2
92	3	3	1	4	2	3	1	2	3	2
93	3	4	3	3	2	1	3	3	1	3
94	3	3	3	4	2	3	1	3	2	1
95	2	1	2	4	2	3	1	2	1	1
96	1	1	3	1	3	2	3	3	1	2
97	4	4	2	1	3	1	1	2	1	2
98	1	2	2	4	2	2	3	1	2	1
99	4	1	4	4	2	1	3	2	3	2
100	4	1	4	3	3	1	3	3	2	1

Table 17. Simulated damage scores and certainty measurements table.

House	Aggregated damage score	House	Aggregated damage score	House	Aggregated certainty value	House	Aggregated certainty value
1	4	**51**	4	**1**	60%	**51**	67%
2	4	**52**	4	**2**	86%	**52**	73%
3	2	**53**	4	**3**	67%	**53**	40%
4	3	**54**	4	**4**	60%	**54**	73%
5	4	**55**	2	**5**	46%	**55**	73%
6	2	**56**	4	**6**	67%	**56**	73%
7	4	**57**	2	**7**	60%	**57**	67%
8	2	**58**	4	**8**	93%	**58**	60%
9	4	**59**	4	**9**	87%	**59**	73%
10	4	**60**	4	**10**	73%	**60**	67%
11	4	**61**	4	**11**	87%	**61**	67%
12	4	**62**	4	**12**	80%	**62**	67%
13	4	**63**	4	**13**	60%	**63**	60%
14	4	**64**	2	**14**	40%	**64**	60%
15	2	**65**	2	**15**	47%	**65**	80%
16	4	**66**	4	**16**	60%	**66**	73%
17	2	**67**	3	**17**	73%	**67**	47%
18	4	**68**	4	**18**	53%	**68**	67%
19	4	**69**	2	**19**	73%	**69**	93%
20	4	**70**	4	**20**	67%	**70**	67%
21	3	**71**	4	**21**	73%	**71**	67%
22	4	**72**	2	**22**	67%	**72**	67%
23	4	**73**	4	**23**	47%	**73**	53%
24	4	**74**	4	**24**	73%	**74**	67%
25	4	**75**	4	**25**	80%	**75**	87%
26	2	**76**	4	**26**	53%	**76**	73%
27	4	**77**	4	**27**	73%	**77**	60%
28	4	**78**	4	**28**	80%	**78**	60%
29	4	**79**	4	**29**	73%	**79**	60%
30	4	**80**	4	**30**	60%	**80**	67%
31	4	**81**	4	**31**	47%	**81**	53%
32	2	**82**	2	**32**	67%	**82**	60%
33	4	**83**	4	**33**	53%	**83**	80%
34	4	**84**	2	**34**	53%	**84**	60%
35	4	**85**	2	**35**	67%	**85**	67%
36	4	**86**	4	**36**	60%	**86**	67%
37	4	**87**	4	**37**	87%	**87**	67%
38	4	**88**	4	**38**	73%	**88**	73%
39	2	**89**	2	**39**	73%	**89**	53%
40	4	**90**	2	**40**	73%	**90**	80%
41	2	**91**	4	**41**	93%	**91**	60%
42	4	**92**	4	**42**	47%	**92**	73%
43	4	**93**	4	**43**	67%	**93**	73%
44	4	**94**	4	**44**	87%	**94**	67%
45	4	**95**	4	**45**	47%	**95**	53%
46	4	**96**	2	**46**	60%	**96**	73%
47	4	**97**	4	**47**	80%	**97**	47%
48	4	**98**	4	**48**	40%	**98**	60%
49	4	**99**	4	**49**	73%	**99**	73%
50	2	**100**	4	**50**	47%	**100**	67%

Table 18. Aggregated values for the damage and the certainty

7.8. Brief presentation of the experts that collaborated in the interface

Greene, Marjorie.
Special Projects Manager at the Earthquake Engineering Research Institute

Mormile, Martina.
PhD candidate at the University of La Sapienza, Rome. Main focus in photogrammetry and UAVs.

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Structural engineer specialized in earthquake engineering at the Cambridge Architectural Research Ltd.

Lemoine, Guido.
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Rossetto, Tizina.
Professor of Earthquake Engineering at the University College London

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Assistant professor at ITC Faculty of Geo-Information Science and Earth Observation of the University of Twente