POLITECNICO DI TORINO

Master´s degree in Civil Engineering

Master´s degree Thesis

Bridges structural health monitoring (SHM) with aid of building information modeling (BIM) and remote sensing technologies

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Abstract

Damage detection and characterization of structures is a key aspect in the field of civil engineering. Structures already constructed as well as new structures should be periodically monitored in order identify possible appearance of new damage and obtain reliable information about its integrity. These monitoring procedures should be applied periodically in time in order to instruct rapid repair treatments and guarantee safety to its users. Following this needs, the Structural Health monitoring (SHM) arises as a process of damage detection and characterization in structures with technologies such as sensors, non-destructive testing, etc. or with simple techniques such as visual inspections.

Given the fact that SHM processes leads to a collection of a vast and variable quantity of data about a structure, the Building Information Modeling (BIM) is starting to gain relevance in this context, as it has already shown its utility to store and manage different type of data during the design stages of a structure.

On specific, the field of heritage building information modeling (HBIM) presents a solution to create accurate models of existing structures. This field uses remote sensing technologies such as laser scanning and photogrammetry for surveying the structures in order to detect its main characteristics with an accurate level of detail.

The aim of this study is to present how remote sensing techniques can be used in the context of HBIM and subsequently the HBIM model can be used as a tool for SHM. With this purpose, this research tests the applicability of these methodologies in two real study cases.

On the first part of this research, beams from the superstructure and from the pier cap of an already dismantled overpass bridge were modeled in BIM software parametrically and with a semi-direct importation from a photogrammetric model. Damage information already recovered from these elements was then transferred into the BIM platform. As a second step of the research, a complete survey of the first span of an existing bridge was done and a 3D model of the structure was created. Then, the process of semi-direct importation from the remote sensing software to the BIM platform was applied. Finally, a user interface was created inside the BIM software so that an operator can characterize and classify the damage directly inside the model, following the approach given by new guidelines from the Italian authorities.

The results of this study show that the modeling of existing structures for SHM using BIM software is possible and can produce a useful tool keep control of existing structures. However, this research also demonstrates that as some compatibility problems between remote sensing and BIM software still exists, the great potential of the combination of these tools for SHM purposes implies significant manual work and that future research on this field is a crucial aspect to initiate developing this methodology as a standard for existing structures.

Keywords: SHM, remote sense techniques, photogrammetry, laser scanner, Inspection and monitoring of bridges, HBIM.

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Introduction

Structural health monitoring (SHM) in the context of civil engineering consists on a series of processes and strategies in order to identify and characterize damage on structures in a correct manner and on time. These methodologies have been gaining relevance in the field of civil engineering, partly, unfortunately, because of a series of tragedies that have occurred due to the lack of maintenance and control of deteriorated structures.

The processes and activities that form part of an SHM methodology may include the use of technologies such as sensors, non-destructive testing, structural models, etc. or more traditional and simple techniques such as visual evaluations of structures. No matter what methodology is decided in order to implement an SHM system, a certain fact is that a vast quantity of information is always recovered and that this information may come from several types of sources and formats. Because of this situation, the storage, compilation and processing of information has become a more and more challenging aspect in the SHM field.

Due to this condition, the building information modeling (BIM) has emerged as a possible solution in order to organize all the information into a single database. BIM methodologies have already been proved useful in the design and construction phases of structures as they allow a digital representation of the structure containing any needed information the construction during its lifetime. However, for the context of SHM its utility is still to be proved.

As SHM systems refer to already constructed structures a specific are of BIM called Heritage Building Information Modeling (HBIM). HBIM aims to create a precise and reliable 3D model of any type of structure in its "as-is" condition starting from survey of data. Different approaches for surveying the structure may be used; however, as these types of models should be as precise as possible remote sensing technologies are preferred because of the vast quantity of information that they can easily acquire in order to create a complete model.

On this sense, photogrammetry and laser scanner are well-known techniques in order to survey any type of structure and create detailed 3D models. The velocity of how a these types of surveys can be done provides a great advantage for the modelation process, as the time saved from the survey procedure can be used to create the 3D model in a correct manner. Nevertheless, as the process of passing from a remote sense model to a BIM platform is still in an on-develop stage, several interoperability problems between software are still presented.

The aim of this study is to test the value of remote sense techniques for BIM modelation and likewise the usage of BIM procedures for SHM. In order to reach this purpose two different study cases are going to be analyzed:

1. The Largo Grosseto Overpass: Largo Grosseto overpass is a dismantled bridge that operated over 50 years in the City of Turin Italy. Due to its large degradation and with the purpose of building a new tunnel on the area, the bridge was dismantled in 2019. Beams from the bridge were left to Politecnico di Torino in order to evaluate the present damage on the bridge at the end of its lifecycle.

2. The Stura River Bridge on the motorway connection RA10: The motorway connection RA10 is a 10km motorway that allows the connection between the city of Turin and the international airport Caselle. On the first kilometers of this motorway, the Stura River is crossed by a 150 meters length, double carriageway bridge. Due to the importance of this bridge, it has been subject of constant monitoring by ANAS, the company in charge of motorway maintenance in Italy.

This thesis is subdivided into five different chapters. On the first one theoretical concepts about structural health monitoring, building information modeling and remote sense technologies are reviewed. The second chapter includes information about the current methodologies for bridges monitoring in Italy, the problem that they present and previous experiences of similar works are included. On the third chapter, the aim of the study is presented as well as the study cases, the software used and the methodology to be followed.

On the fourth chapter, the actual study is developed. The first part of this section refers to the largo Grosseto overpass study case. In this section, the different processes of modelation for this study case are explained as well as the procedures of passing information from traditional means to BIM software. On the second section, the Stura bridge study case is exhibited. This section start from the survey process, passes through the modelation procedures and finalizes with the creation of the user interface in order to characterize the damage directly inside the BIM environment.

Finally, on the fifth chapter the results obtained are discussed, conclusions from the present work are exhibited and recommendations for future works based on the present experience are presented.

Chapter 1: Theoretical Concepts

1.1 Structural Health Monitoring

1.1.1   Context

Throughout the history, structures and infrastructures in the field of civil engineering have been perceived, designed and constructed following different approaches. Nowadays, codes and construction specification around the world require the determination of a life period for any new structure considering the serviceability limit states and its ultimate limit state. However, this situation have not always been like this.

Most of the structures built in the past centuries did not consider all the possible damaging effects and internal actions, as the knowledge in structural engineering was not as advanced as in it is in the present time. Moreover, some more recent structures that have been designed following current approaches, have already fulfilled their life period and are starting to present damaging effects that may compromise the safety of its users.

This problem is of especial relevance in Europe, where the existing structures can date up to five centuries ago and are still on use. In Italy, the maintenance of structures can be of specially significant in economic terms, taking into account that according to the balance given in 2018 by ANAS (the government-owned company in charge of the construction and maintenance of Italian motorways), for maintenance, control and repair treatments of existing road infrastructures a budget of around 1.1 milliard of euros has been assigned for 2018. (ANAS S.p.A., 2019).
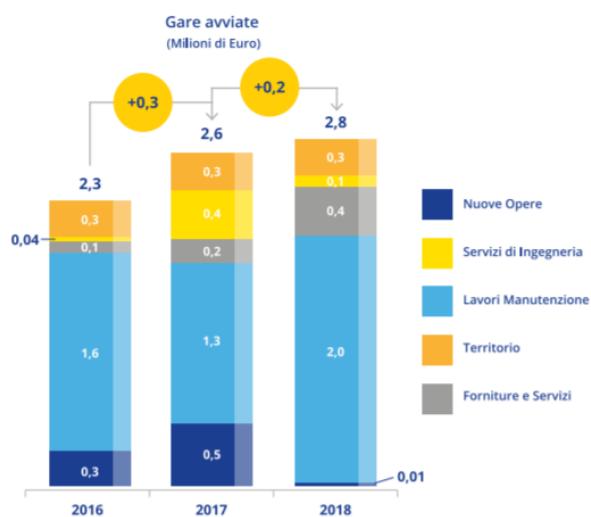
Figure 1. Budget distribution for road infrastructure in Italy. Source: Bilancio 2018–ANAS, 2019. pp.55.

Even with this huge investment in repair treatments and monitoring, some tragedies still happen such as the case of the Morandi Bridge in Genova and more recently the Caprigliola Bridge in La Spezia. This two cases are of important relevance because demonstrate that in Italy new techniques in terms of monitoring and control of health of all structures already built (as well as for the new structures) should be implemented.

Normally, for infrastructure facilities such as bridges or tunnels examination and maintenance routines are developed from time to time. These general inspections may occur at a certain programmed time as regular inspections or as additional surveillance actions outside a predisposed date if some specific problems in performance are observed. Traditional inspections are generally made visually, collecting the damage of the structure by filling out annex charts. In some special cases, the damage characterization may also include the use of no destructive tests and sensors to collect information. Then, according to each specific case, the safety level of the structure is determined and maintenance actions are proposed if are considered needed.

However, there are some issues from this methodology. On the first hand there is no general risk classification of structures, so the damage classification may vary from structure to structure and in some cases it may turns out to be subjective, as there is no general standard. Then, an important difficulty of current methodologies is joining all the information together in a single model, allowing that the information from visual inspections, tests and sensors and its variation on time to be available in a unique file. Additionally, once the structure's damage has been categorized, there is no specific standard on how to model and evaluate this damaged structure in order to check its real characteristics. Finally, there is an absence of a general database for the entire infrastructure present in the network that makes the control and identification of common deficiencies more difficult.

Given these issues, on April of 2020 the new guidelines for bridge monitoring and risk classification were published by the Minister of Transport infrastructure of Italy. The main scope of these new guidelines is to present a multilevel approach for bridge monitoring defining a general methodology for damage detection and risk classification for existing bridges according to qualitative parameters. (Italia, Ministero delle Infrastrutture e dei Trasporti, Linee guida per la classificazione e gestione del rischio, la valutazione della sicurezza ed il monitoraggio dei ponti esistenti, 2020)

Due to this situation, the structural health monitoring (SHM) processes play a key role in order to implement a damage identification and characterization strategy so that updated information about the structure health are stored, managed and used on time to correctly classify the structure and prevent greater damage or collapse situations.

1.1.2   Definition

According to the book New Trends in Vibration Based Structural Health Monitoring written by Farrar and Worden in 2007, SHM can be described in the following way:

"The process of implementing a damage identification strategy for aerospace, civil and mechanical engineering infrastructure is referred to as structural health monitoring (SHM). This process involves the observation of a structure or mechanical system over time using periodically spaced measurements, the extraction of damage-sensitive features from these measurements and the statistical analysis of these features to determine the current state of system health."

On this definition is largely important to recall what the authors describe as damage, being damage defined in the following manner:

"Changes to the material and/or geometric properties of the system, including changes to the boundary conditions and system connectivity, which adversely affect the system's performance".

From this journal, the authors remark that SHM is a process that should periodically update its information regarding the accumulated damage of the structure and its high utility for rapid condition screening after an extreme event, such as an earthquake or unanticipated blast loading.

1.1.3   Visual inspections and image analysis approach for SHM

Visual inspections is one of the oldest and most used inspection methods used. This non-invasive technique consists on the monitoring of structures from a trained inspector by simply overlooking at naked eye for its present flaws as well identifying possible changes in with respect to a previous survey. As simple as this method may look it presents an easy, reliable and cost effective solution for damage characterization of structures. A well-trained inspector can detect most signs of superficial damage in structures, and complementing this strategy with measurements, pictures and image analysis may reproduce a realistic concept of the structure´s damage.

Image analysis and processing refers to the processes of recognizing, differentiating, and quantifying diverse type of images in order to extract significant information from them. In the context of SHM, this aspect is used broadly as an integrated methodology for detection and evaluation of surface degradation in structures.

In current SHM methodologies, the structures monitoring require an inspector to travel to the evaluated structure site and visually report the structure's condition. These visual inspections are complemented with measures, notes and images in order to fill out inspections charts where the damage is described. From this visual analysis, a realistic model of the structure can be created and the safety level can be categorized.

However, these methodologies also present significant disadvantages. On the first hand, these procedures are highly dependent on human subjectivity, so depending on how well trained is the inspector on charge possible inaccuracies, false and missing damage detections may occur. Furthermore, visual inspections may demand personnel to access hazardous situations and environments, which may put them in life risk situations. (Attard et al., 2018)

In order to avoid the possibilities of errors and to ensure the safety of inspectors, new methodologies have been experimentally tested in order to provide alternative solutions for damage detection on existing structures. Research regarding automatized image processing, computer vision, and machine learning techniques for structural analysis, have shown promising results in the field in order to automatically identify and characterize superficial damage in structures. (Koshy et al., 2016). Moreover, photogrammetric techniques have also shown its utility as they provide a fast, timesaving survey technique that allows operators to be on safe positions and appropriately surveying hazardous environments.

Figure 2. Example of automatized image processing for a crack wall. Source: Koshy et al., 2016. pp. 2

1.2 Building Information Modeling

1.2.1   Context

In any construction project developed or in construction phases a large amount of data is generated. All this data may refer to any aspect of the facility characteristics being as wide as from structural parameters to MEP maintenance plans, to cite two possible examples. On the past, all of this information was managed directly by the team in charge of the specific discipline and each one of the stakeholders in the project generated its own type of data, in a not unified format. This methodology made the accessibility, storage and administration of the information an extremely complicated task to accomplish. This problem lead to a necessity in order to collect the information in a unique interactive database, able to share information among different disciplines.

In this context, a Building Information Model (BIM) allows a digital representation of physical and functional characteristics of a facility. As such, it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle from inception onward. A basic premise of BIM is the improvement on communication and coordination by different stakeholders at different phases of the life cycle of a facility to insert, extract, update or modify information in the BIM to support and reflect the roles of that stakeholder.
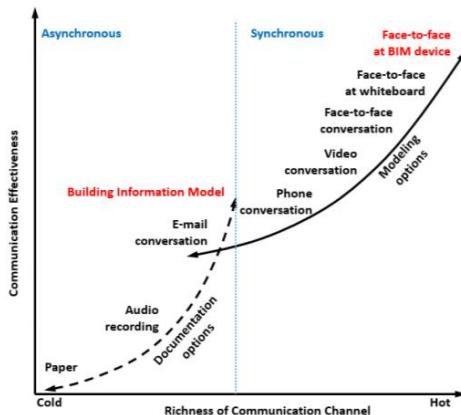
Figure 3. Improvement on the communication channel thanks to BIM. Source: Svalestuen et al., 2017. pp. 5

In some countries like United States, Canada, Norway, Finland, Denmark, Australia and the United Kingdom, BIM is already implemented as a mandatory requirement in public and private works. In Italy, according to the "*Decreto Ministeriale MIT n.560 del 1/12/2017*" the Italian Ministry of Infrastructure set a plan for introducing BIM as mandatory requirement for public processes. The plan starts from 2019 for projects above 100 million,

continuing with a series of a several deadlines through the following years, ending with full implementation by 2022, when BIM will become compulsory for all public procurement projects.

1.2.2   Definition

The concept of BIM can be understood with a double meaning, as an activity (Modeling) or as a representation platform (Model). The concepts described on the following section are taken from the lectures notes of the course *BIM and InfraBIM for built heritage* by professor Osello, from the Politecnico di Torino.

One of the most precise definitions of Building information modeling from these lectures is the following one:

"Building information modeling is a method that is based on a building model containing any information about the construction. In addition to contents of the 3D object-based models, this is information such as specifications, building elements, specifications, economy and programs."

On the other hand, an accurate definition Building information model is the following one:

"A building information model is a digital representation of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle, from inception onward"

Referring to the building information model, a very important concept to consider is the level of detail (LOD) to be present in the model. The LOD refers to the quantity and quality of information content that serves to achieve the goals of the process phases and the model goals. According to the methodology ISO 19650 the LOD of a model can be defined taking into account as the level of information need (minimum amount of information needed to answer each relevant requirement).
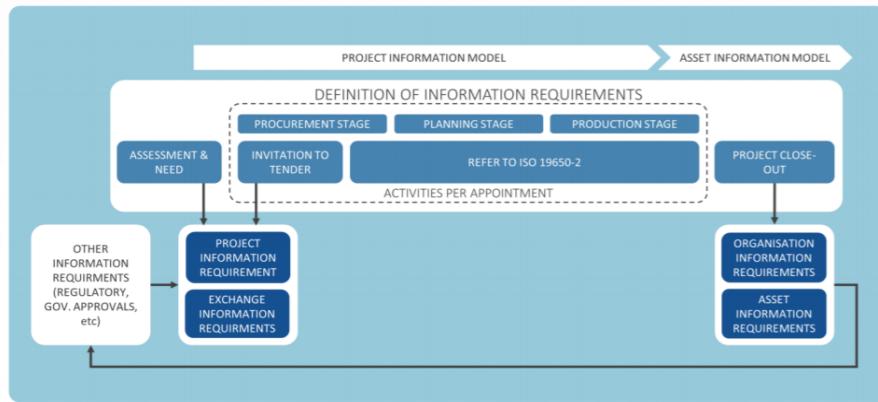
Figure 4. LOD definition from Australian guide to ISO 19650. Source: Brook et al., 2019.

Then, taking into account, that life cycle of civil structures consider many phases from its conception and design until its operability in service life, this several phases are taking into account considering a subdivision of BIM in seven different dimensions.

Table 1. BIM dimensions

First dimension	Refers to the initial idealization of the project, considering preliminary requirements in terms of geometry, materials, location, usage of the facility, costs, etc.
Second dimension	Refers to the determination of the general characteristics of the facility. During this phase, the basic information about a building in terms of geometry, materials, cost and any general requirements is determined. The amount of information recompiled during this phase is not standard but varies from project to project.
Third dimension	Refers to the gathering and merging of the previous information into a single 3D digital model. This 3D model should allow different team members to recover and input information simultaneously and modify it at different time stages.
Fourth dimension	Refers to the inclusion of the temporal dimension into the model. The fourth dimension make reference to a time-dependent view of BIM in which objects are associate with activities from construction plans and animation, and space-time conflicts may be checked.
Fifth dimension	Refers to the inclusion of the estimation and cost analysis to the model. A cost-dependent view of BIM where budget line items are associated with model objects allows more accurate estimations and control of cost analysis during the facility phases.
Sixth dimension	Refers to the sustainability of the structure on time. This dimension ensures accurate predictions and simulation about the structure life cycle needs taking into account diverse aspects such as energy estimations and consumption requirements.
Seventh dimension	Refers to the inclusion of facility manage information in the model. This dimension is used to manage data such as the facility components status, its maintenance/operation manuals, its warranty information, technical specifications, etc. to be used at a future stage.

1.2.3   HBIM, as-is models

Considering that the modeling process is different for an existing structure for a new building, a new field in the area of BIM called Historic or Heritage building information modeling (HBIM) has been developed in the recent years. This area of BIM targets to construct a reliable and precise record of the building in its as-is condition starting from a geometrical survey of data instead that from a project idealization.

Ordinary information for HBIM may include geometrical data, architectural style, material characterization, façade complete representation (including its degradations and interventions), damage survey and plan of interventions, risk and safety assessment of the structure, environmental parameters and maintenance plans. (Pocobelli et al., 2018).

As occurs in traditional BIM models, the model maturity level needs to be considered also on this case. Considering the specified level of detail wanted for the model, different approaches for surveying the structure (detecting its dimensions, geometry, materials, etc.) may be used.

Traditional survey approaches are carried out by using the triangulation methodology, which consists of manually taking angle measurements and fixing reference-points (stations) in order to get distances, levels and determine the location of a structure. However, with the improvement of remote sensing technologies new approaches for surveying are playing key roles in the field on the last few years. More specifically, technologies like 3D laser scanning and photogrammetry surveys have proven to be extremely accurate at registering non-regular geometries and surface textures of structures while being cost effective and time saving methodologies. (El-Din Fawzy, 2019).

The output generated by these remote sensing technologies usually is a dense point cloud (a set of data points in the space), which needs to pass through a post-processing procedure. The most common operations of post-processing may include noise elimination, point cloud registration and creation of triangulated surface.

After these post-processing procedures are applied, the model is taken into a BIM environment, where all the complementary information is added in order to create a complete database.

1.3 Remote sense technologies

1.3.1   Context

The remote sensing science consists on the acquisition of any type of information about areas or objects from a certain distance and without making physical contact with the surveyed object. Due to this broad concept, this science can date back in history to early times. From renascent times concepts of perspective and geometry projections have been developed, which ultimately set the basis for photogrammetric theory. Then, with the invention of the camera and the technological evolution of photography processes huge advances on this field were made. On the other hand, the military needs during war periods found in remote sensing methodologies a great resource to determine the advantage against the enemy. Initial radar detections and radar imaging systems were later further evolved on civil applications for data acquisition such as exploration mapping and accurate measurements. The improvement of remote sense survey procedures advanced to a point where they became a standard technology for objects acquisition, including also specialized computer software in order to generate representative models. (Klinkenberg, 2017).

In the context of civil engineering, two of the most used remote sensing techniques are photogrammetry and 3D laser scanner. These procedures are considered mass collection techniques as millions of information resources are obtained from a single survey. Information about geometric, physical, semantic and temporal characteristics of the surveyed object should be obtained. The final product expected from these surveys can vary from photographic products, digital elevation models, topographic maps, dense point cloud or 3D objects.

On this sense, the models generated through remote sensing methodologies provide significant advantages with respect to traditional survey methods. Some of the more categorical advantages can be:

- The ease and speed at which large amount of data is collected.
- It represents a low cost solution for accurate data acquisition.
- Produces high precision measurements, acquisition of 3D geo-data and construction of representative 3D models of reality.
- The acquisition of permanent photogrammetric record with metric properties that can be further re-surveyed or re-analyzed.
- Its usefulness in any type of locations regardless of position, access or dimensions.

-   The flexibility of its output allows its convenience in a different vast number of fields (topographic or non-topographic).

Specifically, for structural engineering, the purpose of these techniques is usually to create a 3D point cloud that reconstructs the geometry from the surface of the subject. These points can then be used obtain detailed information about several aspects, taking into account that they contain information about the color and shape of the subject.

These techniques have gained important notice as they allow the accurate monitoring of large structures on time. The recollection of an unlimited number of points by these procedures, allow the easily and fast reconstruction of structures in order to monitor measurements, displacements, deformations and settlements. Moreover, the recreation of an accurate 3D model provides an easier assessment to the construction projects, improving its visualization on a systematic basis and its further evaluation when already constructed.

On the following sections, photogrammetry and 3D laser scanner techniques are going to be further explained, as they are the remote sensing procedures used on this research.

1.3.2   Photogrammetry - Definition

There is no universally accepted definition of photogrammetry; however, the following description given by Wolf et al. (2000) captures its primary notion:

"Photogrammetry is the art, science, and technology of obtaining reliable information about physical objects and the environment through processes of recording, measuring, and interpreting photographic images and patterns of recorded radiant electromagnetic energy and other phenomena."

Photogrammetry works based on the principle of collinearity. This principle establish a relation between images and object space points. In photogrammetry, if an object is present inside at least two different images it is possible to retrieve metric information about it using mathematical principles. Subsequently, as it happens in human vision, if the two images are taken from different points of view, it is possible to derive 3D information about it.
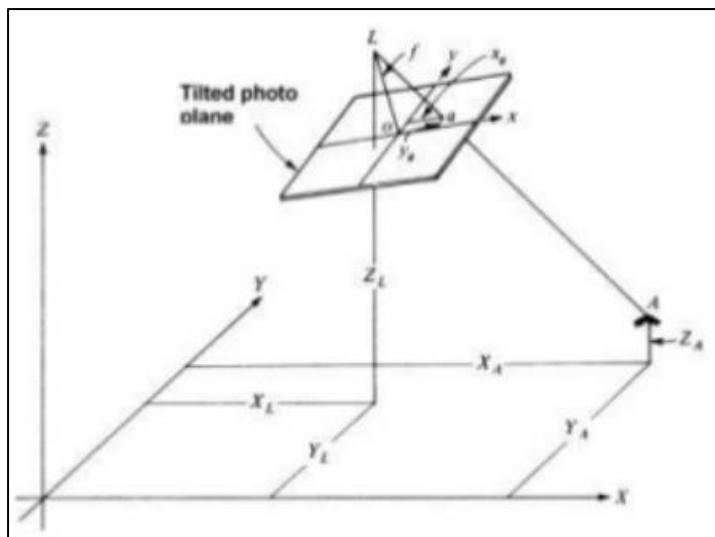
$$x_a = x_0 - f \left[\frac{m_{11}(X_A - X_L) + m_{12}(Y_A - Y_L) + m_{13}(Z_A - Z_L)}{m_{31}(X_A - X_L) + m_{32}(Y_A - Y_L) + m_{33}(Z_A - Z_L)} \right]$$

$$y_a = y_0 - f \left[\frac{m_{21}(X_A - X_L) + m_{22}(Y_A - Y_L) + m_{23}(Z_A - Z_L)}{m_{31}(X_A - X_L) + m_{32}(Y_A - Y_L) + m_{33}(Z_A - Z_L)} \right]$$

Figure 5. Collinearity principle and equations. Source: Habib, et al. 2000.

Taken the collinearity principle into account, it is understandable that a complete photogrammetry survey needs a variable quantity of photographs with enough information overlap between them in order to capture the complete geometry of the surveyed object. Then, these images are processed in specialized software that uses these collinearity equations in order to re-create the 3D model. Moreover, if the photogrammetric survey is accompanied by a georeferencing procedure, such as a topographic survey or the usage of GPS/GNSS and ground control points, the 3D object created can be improved to obtain reliable information.

Georeferencing is used in order to establish a relationship between images and object coordinate systems. In this way, a topographic framework is created and the 3D model can be put into a correct scale factor and orientation. Moreover, the usage of a topographic framework with a unique reference point allows the combination of separate point clouds taken from different surveys. Performing computer algorithms such as the Iterative Closest Point (ICP) the different point clouds can be merged into a single one and a more complete and robust model can be created.

Photogrammetry can be classified depending on many factors. The following of photogrammetry is given on the book Geoinformatics by Chandra (2016) and on the specialized research portal *Gisresources*:

Metric photogrammetry: Involves all quantitative works, such as determination of ground positions, distances, areas, volumes and preparation of various types of maps.

Interpretative photogrammetry: Consists on identifying objects and assessing their significance through systematic analysis from photographic images.

In addition, a further subdivision depending on the camera location can be done in the following manner:

Aerial photogrammetry: Aerial photographs are a set of multiple overlapping photos that are taken from the air by a moving aircraft flying over the survey area. The aircraft in charge of the survey is equipped with a special camera positioned with its axis in vertical position or nearly so. These photos taken are usually latter post-processed in a stereo-plotter. Platforms for aerial photography may include aircrafts, helicopters, unmanned aerial vehicles (UAVs), balloons, blimps, etc.

Terrestrial photogrammetry: Terrestrial photographs are taken from a ground site or near ground site with a camera axis positioned horizontally or nearly so. The position from where the photographs is taken is fixed and most of the times should be a known position.

Space photogrammetry: Extraterrestrial photography occurs when the camera is positions in a fixed position, but this position may vary from the earth, to be contained in an artificial satellite or aircraft, or positioned on natural satellites or even other planets.

It is also important to point out that a photogrammetry survey may be limited by visibility and lightning conditions. For a photogrammetric survey to be performed correctly, its necessary to ensure optimal weather and lightning conditions are necessary. These conditions are of such importance that on circumstances where natural lightning is not optimal, artificial lightning options should be evaluated to improve the image capturing. Moreover, it should be ensured that all the geometry from the surveyed object is captured by the images with enough information overlap and avoiding large information voids between photos. Finally, notes and measurements should be taken in order to complement the survey. (Rocha et al., 2020).

1.3.3 LiDAR and Laser scanner – Definition

LiDAR (Light detection and ranging) and laser scanner are techniques that allows the acquisition millions of 3D point in an automatic or semi-automatic manner, with each point containing a known position (in local Coordinate System) and color information (If the

instrument is also equipped by a digital camera). These techniques are based on the measurement of distances using the electromagnetic wave, also called as Laser (Light amplification by simulated emission of radiation). A further explanation on the working principle for laser scanner techniques is explained by Royo and Ballesta-Garcia in 2019:

"LiDAR stands on a simple working principle based on counting the time between events in magnitudes carried out by light, such as e.g., backscattered energy from a pulsed beam. From these time measurements, the speed of light in air is used to compute distances or to perform mapping."

The measurement of distance is achieved by measuring the time required for the transmitted signal to return to the receiver and modulating three different parameters: Intensity, phase, and/or frequency. Hence, three different approaches can be derived from LiDAR procedures.

On the first one, the arrival time of the pulse's echo to the receiver is used to determine the distance. This methodology allow reaching long distances while maintaining a centimeter resolution. The second methodology is based on amplitude modulation of a continuous wave, so the phase of the emitted signal is compared to the wave of the received to measure the distance. A centimeter precision can also be achieved on this case, but long distances are difficult to reach due to the ambiguity in frequency modulation. A final approach consist on the modulation and demodulation of the signals in the frequency domain. This approach is based on the superposition of the emitted and detected wave to detect the distance. With this final approach resolutions below the first two approaches are obtained, however, using physical concepts such as the Doppler effect, velocimetry measurements can be automatically obtained.
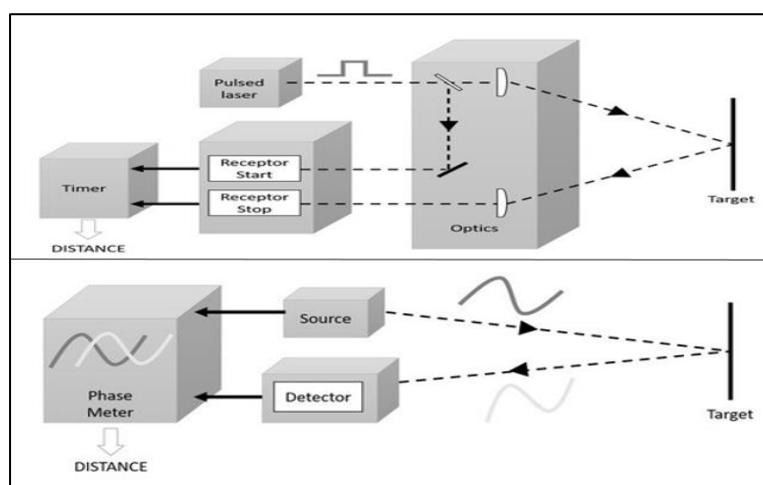
Figure 6. Schematic image of the first two working principles for LiDAR. Source: Royo and Ballesta-Garcia, 2019.

In all cases, the acquisition of information for a LiDAR system is made through instrumentation called laser scanners. These Laser scanners produce a laser impulse that is guided by small rotating mirror controlled by servomotors. In this way, these rotating mirrors produce a series of columns of sequential points that move over the surveyed object in order to create a complete "laser paint". With these methodology millions of point can be recovered in a minimal amount of time in order to create a 3D spatial point cloud, where each point is provided with coordinate (X, Y, Z) and color information (RGB) if the instrument is also equipped with an automatic digital camera.

Laser scanners present a significant advantage to rapidly determine with high accuracy and high resolution 3D information, however as this methodology is based on light measurements to collect data, situations were too much ambient light is present or shiny/reflective surfaces are surveyed, may produce a distorted final model. Because of this constrain, less illuminated scan areas are preferred for laser scanner surveys that can then be complemented with photogrammetric surveys to obtain color and texture information to complement the 3D model.

1.3.4 Remote sensing and implementation of HBIM

The integration of photogrammetry and laser scanner in the BIM workflow represents a powerful technique to document the condition of any structure in its current state in a very precise manner.

Through the help of this technology many advantages arises on the implementation of HBIM. On the first hand remote sensing procedures require a small amount of time compared to traditional survey processes, making more time available for other processes, such as the modeling of the structure. Another big advantage is the higher accuracy and low cost of these methodologies with respect to traditional surveys. Finally, the fact that the output generated is a complete, high-quality three-dimensional model represents a powerful tool for the identification, classification and conservation of structures. (Pocobelli, 2018).

When creating HBIM models with aid of 3D objects generated by photogrammetry and laser scanner different modelation paths can be followed. Depending on the modelation path chosen, different characteristics and elements of the original 3D model are passed to the BIM environment. These paths can vary significantly not only in the quantity of information transmitted, but also in their time efficiency, automatization and computational requirement. The quantity of information to be passed can be as variable as theoretically passing all the

information from 3D model about geometries, shapes, color and texture with a direct modeling methodology, or using the point cloud only for comparison purposes of objects created directly on the BIM environment with the parametric modeling methodology. (Tommassi et al., 2016).

Nevertheless, the application of remote sensing in HBIM is far from being perfect because the interoperability between survey tools and modeling software is still significantly limited. Quoting the academic research made by Tommassi in 2016:

"The actual reduction of time from survey and acquisition of dense but rough three dimensional measurements – Point clouds- collides with modeling operations which are still largely manual and costly in terms of time-consuming and technology resources".

Other problems that may emerge due to the use of survey data is the difficulty on managing big size data files and the lack of a generalized workflow in order to apply this methodology.
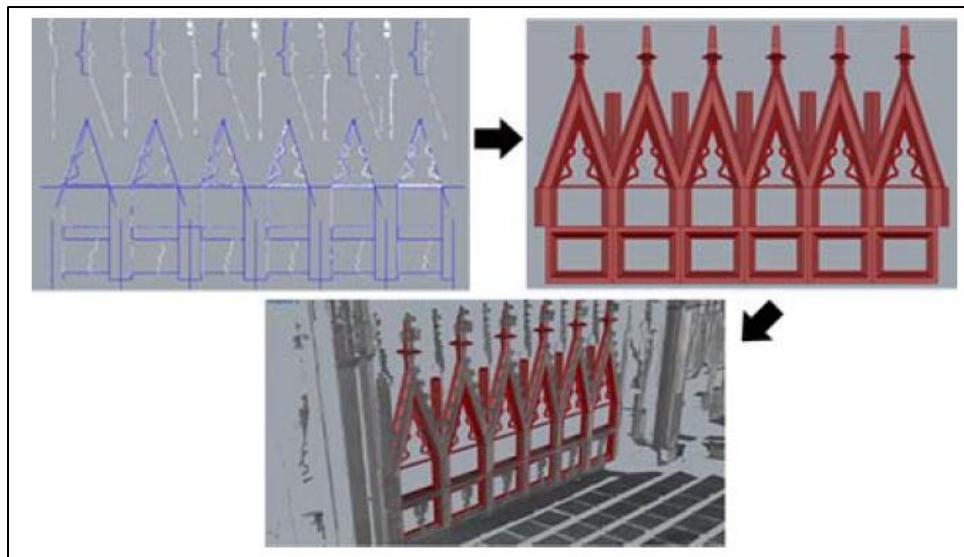
Figure 7. Example of a photogrammetric to model case. Source: Tommasi et al. (2016).

Chapter 2: Guidelines for bridge monitoring, existing problems and previous experiences

2.1 Previous methodologies for bridges SHM and existing problems

Damage characterization and maintenance procedures may vary significantly depending on the type of structure and the country where the structure is located. On this section, bridges SHM procedures in Italy are going to be described, as they result more relevant considering the study case of this research.

On the past years the guidelines for inspection activities on bridges where indicated by the *"Circolare Ministerio dei Lavori Pubblici n. 6737/61 del 1967"*. This document indicates general procedures for monitoring activities that include the following actions:

- Four annual inspections made by specialized technicians and one of them made by an engineer to all bridges with span length greater or equal than 10 meters.
- Non-destructive testing to support rehabilitation activities.
- Geotechnical monitoring through visual, instrumental and geognostic surveys.
- Hydraulic inspections and classification to all bridges independently of its span length.

With the results by these inspections, the state of the structure was determined by the engineer on charge and consistent actions to be followed where determined (e.g. planning of future interventions)

Unfortunately, as recent unexpected collapses of bridges have demonstrated in these previous years, these plans have not been enough to correctly monitor the infrastructure network. An important problem regarding this methodology was that it only specified general activities and did not count with a specific qualitative method that could be used for any type of bridge regardless of its typology. Consequently, damage assessment and risk classification of structure was very susceptible to individual notions given the respective study case.

Considering this problem, a smarter SHM methodology was adopted on 2020 with the implementation of the new guidelines for risk management, safety classification and monitoring of existing bridges. (*Linee guida per la classificazione e gestione della sicurezza e il monitoraggio dei ponti esistenti*). The main objective of this guideline is to provide a

homogenous, uniform, qualitative method in order control and monitor existing bridges regardless of its different typologies.

2.2 Current guideline for bridges monitoring and inspection

The new guideline illustrates a procedure based on three components: Risk classification, safety assessment and Inspections/monitoring. Based on this, six different levels of analysis can be reached:

Table 2. Levels of analysis given by current monitoring guideline.

Level 0	Includes the census, geo-localization and general characterization of all the bridges in the Italian network, as well as the gathering and collection of all the information considering the existing documentation.
Level 1	Includes the realization of direct visual inspections, the realization of photographic and geometric survey of the structure and the geo-morphologic characteristics of the area to individuate the damage state and the principal structural and geometrical characteristics. For bridges in pre-compressed concrete, bridges in post-tensed concrete or any type of bridge in area of landslides, flooding or erosional danger special inspections are also intended where non-destructive and semi-destructive testing must be done.
Level 2	Consists on classifying the bridge according to vulnerability, exposition and risk parameters based on the information obtained from the previous levels. Based on the classification given on this level, the following levels to be implemented are chosen.
Level 3	Consist on preliminary evaluation of the typology and profundity of the damage detected on level 1 and aims to determine if further and more accurate verifications should be performed.
Level 4	Consists on the realization of accurate verifications based on the existing normative *"Norme techniche delle costruzioni"*. On this level, non-destructive testing could be introducing in order to further verify the damage profundity.
Level 5	Is not treated in the current guideline as it refers to bridges of particular importance on the road network and a more refined specific study should be applied.

As it can be seen from the previous table, on level 0 and level 1, most of the information from the SHM of the bridge is recovered and from level 2 the bridges are classified according to vulnerability (level of damage, damage evolution, static scheme, materials span length), exposition (daily average traffic and span length) and risk (typology and amount of present loads). According to this classification given on level 2, further actions are determined or a maintenance plan is set. Taking these indications into account, the possible classification of bridges given on level 2 by the guide refers to five attention classes (*CdA) (abbreviation given the original language).*

- High attention class (*Alta):* For bridges on this category immediate further accurate safety evaluations (level 4) are needed either in terms of geotechnical characteristics or in structural characteristics. The realization of ordinary periodic evaluations is also intended for this level.

- Medium-high attention class (*Medio-alta):* For bridges on this category further accurate preliminary safety evaluations (level 3) are needed. Based on the results obtained from level 3 evaluations, the corresponding entity may decide if it is needed to realize further accurate safety evaluations or not (level 4). The realization of ordinary periodic evaluations is also intended for this level.

- Medium attention class (*Media):* For bridges on this category further accurate preliminary safety evaluations (level 3) are needed. Based on the results obtained from level 3 evaluations and on the evolution of the present damage on time, the corresponding entity may decide if a system of extra-ordinary evaluations is needed.

- Medium-low attention class (*Medio-bassa):* For bridges on this category, no further safety evaluations are intended different from the ones executed on frequent periodic inspections.

- Low attention class (*bassa):* For bridges on this category, no further safety evaluations are intended different from the ones executed on not-frequent periodic inspections.
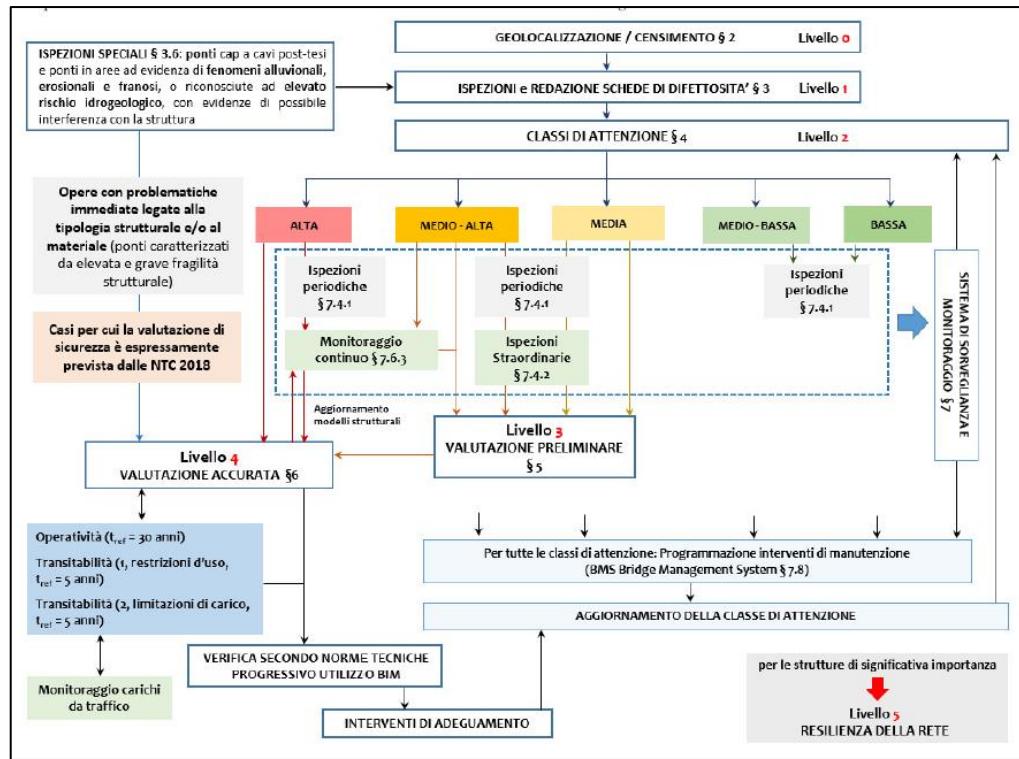
Figure 8. Workflow given on current guidelines for bridge safety classification. Source: (Linee guida per la classificazione e gestione della sicurezza e il monitoraggio dei ponti esistenti, 2020).

2.3 BIM and remote sensing utility for SHM process

2.3.1   Context

Taking into all the information that needs to be recovered considering the previously described guideline, BIM methodology results helpful as it allows a digital representation of all project data in a single database, making it easier to store, manage and even actualize according to the facility service life. Another big advantage of usage of BIM methodology is its capability for visualizing the structure globally but also individuate single elements when it is needed. This characteristic allows the display of a "big picture" of the structure as it is on reality without losing information about the details of its single elements.

As SHM refers to damage control of existing structures, it is especially relevant the fidelity of the "As-is" model of the structure. Keeping in mind that when studying damage such as cracks or delamination the quality of even the minimal detail is necessary for the correct interpretation of data, it results essential to use technologies that make possible the generation of a model as realistic as possible.

In particular, this level of detail (LOD) represents one of the biggest challenges in the creation of the BIM model and different technologies should be evaluated for this task. In

particular, this investigation refers to a photogrammetric and laser scanner approach in order to represent with a high level of fidelity the model.

Laser scanner and photogrammetry have proved to be technologic resources that allows achieving a high level of precision and capturing enormous quantity of details even in non-regular geometries, that otherwise would not be possible. (Rocha, 2020). As an outcome from these type of surveys, a dense three-dimensional point cloud (a set of data points in space) should be obtained. From this point cloud, 3D models can be created in order to analyze the geometrical and physical surface characteristics of the surveyed object in a correct manner.

This realistic outcome presents an enormous advantage in the monitoring and inspection of damage in structures as it allows the damage detection to be made directly on the model and not always necessarily on the field. This means, that with a complete survey the damage detection can be easily made directly on the model regardless of its position, access or dimensions, contrary of what happens on the field. On the contrary, a big disadvantage on the combination of remote sensing with BIM methodology is the lack of interoperability between software, making the modeling process sometimes even impossible. Specifically, according to Tommassi et al., 2016, when working with point clouds in BIM environment, it is possible to subdivide the software into four different categories:

Table 3. Point clouds on BIM environment software.

Type of software	View/editing software	Modeling software	CAD Software	BIM software
Description	Allows the viewing, exploration, measuring, optimizing and editing of data.	Allows the creation of a surface mesh (3D models), its editing, and the generation of a texture.	Allows the importation of point cloud or the 3D mesh in order to create 3D profiles or create object layers.	Allows the importation of the point cloud (not the 3D object) and the insertion of several other information into the model
Software Examples	AUTODESK RECAP PRO / FARO 3D VISIONARY	PHOTO / Meshlab	AUTOCAD / SketchUp	AUTODESK REVIT / ALLPLAN A NEMETSCHEK COMPANY

2.3.2 Previous experiences of remote sensing for HBIM

As refers to previous experiences of combinations of photogrammetry and laser scanner surveys and BIM, different paths have been followed. A general explanation of the process to be followed is given by Palestrini in 2018.

The first step is the geometric survey of the element. The number of pictures or scans to take during this activity depend on the complexity of the object to survey and the terrain conditions found on site. In all cases, the complete geometry from the surveyed object should be captured in the photographs or the scan, ensuring that the light conditions when the information is retrieved is ideal. The remote sensing survey should be accompanied by a topographic survey to create a topographic framework and set the relationship between images/points and the object coordinate systems. After the survey is completed, the next step covers the creation of the 3D dense point cloud through computational algorithms in specialized software.

Once the 3D dense point cloud is obtained, the proceeding steps involve georeferencing of the model (merging the information from the topographic network with the information from the photogrammetric/Laser scanner survey) to obtain the correct scale factor and orientation and the compressing and optimization of the model in order to obtain a more size-reduced file. Then the optimized point cloud is imported into a dedicated software for the 3D object creation. This 3D object is created thanks to elementary vector and geometry algorithms that produce a triangulated irregular mesh from the points. This mesh is created considering each point of the point cloud as a vertex of an irregular polygon with z coordinate, transforming the point cloud into a polygonal model. It is important to clarify that as the point cloud generated by remote sensing consist on "disordered" points, irregular polygonal meshes are obtained with more small sizes triangles where more points are and less, bigger triangles where less points are located. On this phase, it is also created the "texture" of the geometric model. This texture is created by means of orthographic projections using the UV map of the color data deriving from the photos taken for the survey. This mesh model as well as the texture can also be edited so that the digital noise (other non-necessary elements on the model such as vegetation) is eliminated and the correct orientation and scale factor is set, in case that the model is not georeferenced previously. Finally, this 3D object is used as the basis for the modeling of the HBIM elements. On this final step, the following different methodologies can be followed:

- Direct modeling: This procedure consists on the direct or semi-direct (when the object passes through more than one software before its final importation platform) importation of the 3D object and texture into the BIM software and then adding the additional information for the completeness of the model. Theoretically, with this procedure all the information about shapes, geometry and color is maintained. A reference example for direct modeling from 3D objects software to BIM was exposed by Tommasi et al., in 2016. In this work the authors used the software Rhinoceros and Arena 4D in order to create and model the point cloud. Then this model was exported into Revit to evaluate add all the subsequent information of a BIM system. On this procedure, the authors describe the interoperability problems as the software Rhinoceros uses NURBS (mathematical functions) for the 3D models while Revit uses meshes (Poly-triangular surfaces). In order to make this importation, the formats SAT and IFC were tried. However, with both formats interoperability problems were found as only the shapes were maintained, but the subdivision of the 3D object and the possibility to further edit them or add them materials is not possible. (Tommassi et al., 2016)

- Modeling BIM elements through NURBS: The procedure of modelation of BIM geometries by NURBS (mathematical functions used in CAD software to model 3D curves and form complex forms) consists on the extraction of NURBS curves from the point cloud and the use of this preliminary set of curves to generate a "skeleton" and create a surface in BIM environment. An interesting example of this methodology is described by Barazzetti et al. in 2016. In this work, the authors performed a methodology in order to modelate an historical bridge. The procedure followed consisted on subdividing the bridge point cloud into its basic structural elements (foundation, arches, columns, beams, deck, etc.). Then the authors used computational algorithms in order to obtain a vast range of shapes of the bridge, preserving its mathematical parameters (control points, weights and degree). With the NURBS curves obtained, its parameters were used to generate the shapes in the BIM software, Autodesk Revit and then further geometric data and attributes were included. With this methodology, real shapes and geometries could be maintained, however, materials and textures are not, as the elements are created directly on the BIM platform. (Barazzetti et al., 2016).

- Parametric modeling: This methodology consists on working through pre-established native BIM shapes that are editable by the insertion of parameters. This native BIM shapes are overlapped with the point cloud and are statistically compared to check the accuracy of the model. Another approach for this methodology consist on the importation of the point cloud to the BIM platform and the usage of SCANtoBIM complements to automatically create the geometry. These types of software allows the automatic creation of elements in BIM platform from the point clouds inserted, but, as the geometries are created inside the BIM software, only basic planar shapes and elements are recognized by the software and does not works correctly for complex geometries. An example of this methodology can be retrieved from an academic paper by Rocha et al. in 2020. In this work, the authors generated the point cloud of a building using the Faro Scene software. Then, the point clouds were georeferenced, merged, cleaned, compressed and subsampled to be further manipulated. After these procedures are done, the point cloud is inserted into Revit and the modeling procedures start. The primary levels of the building are created and the reconstruction of the geometry of the building is done parametrically creating custom-made Revit families. Finally, statistically tests are performed in order check the deviation between the elements created on Revit and the original point cloud. (Rocha et al., 2020).
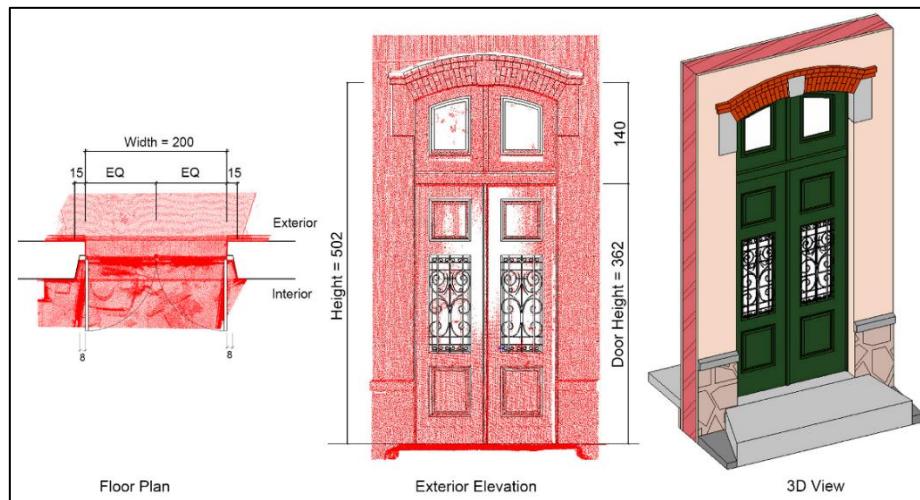
Figure 9. Example of parametric modeling and comparison with point clouds for a given case study. Source: Rocha et al., 2020.

2.3.3   Previous experiences of BIM for SHM

Considering previous experiences with the usage of BIM for SHM, the principal works have focused mainly on aspects regarding the utility of BIM for facility management procedures. In general, BIM methodology as facility management tool has been used as instrument for the generation of plans and methodologies from the design phase, specifying when and how the maintenance procedures of the structures should be realized. In fact, Arditii and Nawakorawi (1999) claimed that 50% of the maintenance-related problems could be eliminated if design defects can be prevented during the design phase.

Taking this approach into account, a great part of the previously made researches focuses on the creation, storage and utility of BIM to keep facility management data for the structures through its lifecycles. A related work on this sense was made by Hosseini et Al., in 2017. In this paper, the authors developed a typology matrix in order to capture the complex relationships between the facility ownership, their users and the data and information needed. This matrix was subdivided into four categories (Developer, occupier, owner, owner-occupier) and determined the policy framework for facilities information and data management requirements. The idea was that the matrix helped its users to list the required data and information needed on the BIM process and how responsibilities for these management requirements are distributed. Consequently, the maintenance, operational activities, SHM methodologies and in general facility management information is determined and the procedure in order to include them into a BIM methodology is explained. (Hosseini et Al., 2017).

Another approach more on going with the usage of BIM for SHM purposes in existing structures consists on the creation of a structural health database where real time information can be periodically actualized to the BIM model. On this way, previous work have mainly focused on the use of sensors on existing structures. With aid of these sensors, data collected from temperature, structural requirements, accelerations, etc. is assigned to different element instances in the model, creating parameters for its control and visualization. An important previous work on this topic was made by Del Grosso et al. in 2017. In this paper, the authors created a bi-directional data flow between BIM and SHM sensors data. To do this communication link the authors analyzed a bridge that had previously been installed with sensors (accelerometers) and recovered information. The authors created a sensor system family in Revit an associate it with updated information coming from measurements on field. Using Excel as a communication interface between the BIM model and the SHM data the model could be further updated according to the information actualization. Finally, in order to

obtain a better visualization of the model and the data included, the authors exported the model into the software NavisWorks 3D viewer. (Del Grosso et al., 2017.).
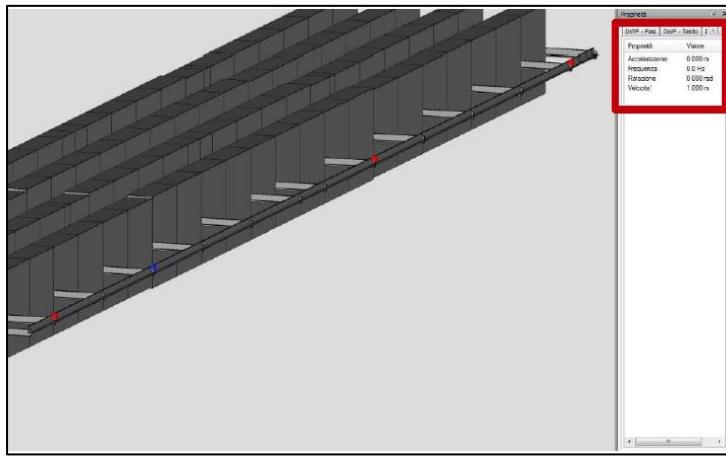
Figure 10. Example of the visualization of sensors family and information. Source: Del Grosso et al., 2017

This research by Del Grosso touches an important aspect in the implementation of an SHM system with aid of BIM methodology, which is the communication link that were created between data recovered on field and the model created. On this sense, the author create a data flow between sensors and the BIM model using Microsoft Excel as a communication medium. This possibility of data flow towards and from the BIM software opens up big possibilities for the quantity and type of information from SHM that can complement BIM software. On this case, the author supplemented the BIM model with SHM information coming from accelerometers; however, the model can be complemented with any type of information regarding the SHM of the system such as traditional monitoring inspections or results from non-destructive testing. On the same way, the fact that the BIM software can transmit information to external platforms also opens up the possibility to use it as a base for several SHM activities such as visual inspections or structural modeling and analysis.

Chapter 3: Objectives of the present study, study cases and proposed methodology

3.1 Objectives of the present study

Considering all the arguments previously said, which demonstrate the value of remote sensing for BIM modelation and likewise the use of BIM for SHM, the aim of this study consists on testing its practical application on two different study cases.

On the first study case, a 3D model and database of damage for the structural elements (beams) of a dismantled bridge is going to be created using BIM methodology. In order to create the beams model two different methodologies are going to be applied: 1) A parametric methodology based on the importation of previously recovered information and 2) A semi-direct importation methodology based on a photogrammetric approach.

On the second study case, a complete laser scanner and photogrammetric survey of the first span of an existing bridge is going to be made in order to create a point cloud and a 3D model. Then, this model is going to be taken into BIM software with a semi-direct importation methodology in order to analyze its present damage. For this purpose, a user interface is going to be created directly on the BIM software using visual programming tools so that the inspector can add all the parameters required according to the new Italian guidelines and export the results into Excel when the bridge inspection is finished.

At the end, the utility and the applicability the previously described techniques is going to be evaluated, and further conclusions and recommendations are going to be given taking into account the obtained results.

3.2 Cases of study

3.2.1 Largo Grosseto Overpass

The overpass Largo Grosseto was an urban bridge in the city of Turin, Italy designed and constructed in the decade of 1960. The bridge operated over 50 years communicating Corso Potenza and Corso Grosseto providing an important exit/entry pass to North West Turin.
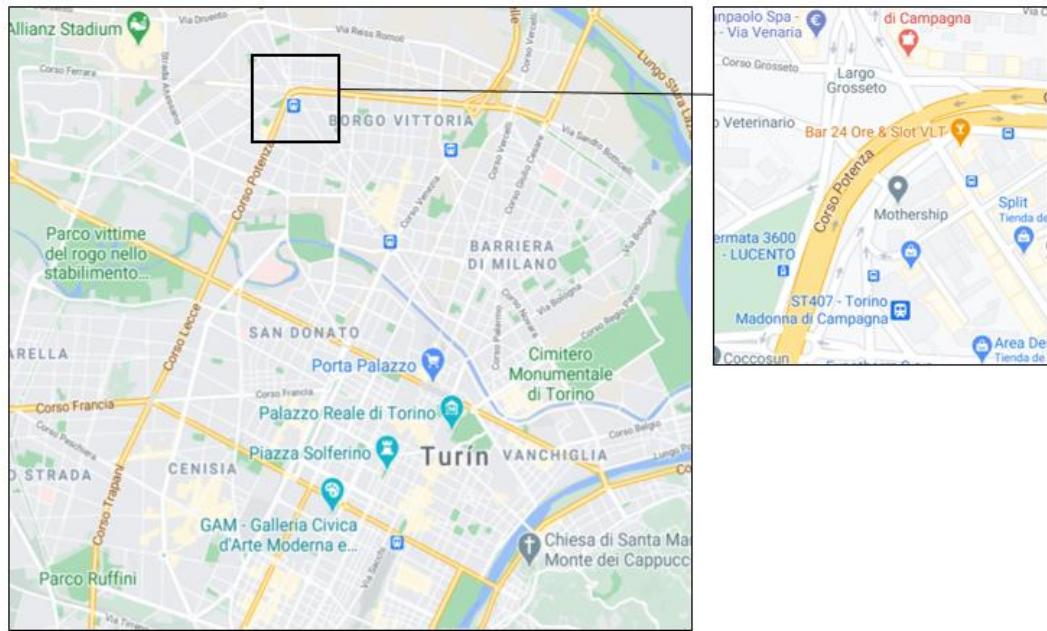
Figure 11. Location of the overpass Largo Grosseto during its life service.

Figure 12. Largo Grosseto Overpass during its life service and during its demolition.

According to the structural calculation report, the flyover had span lengths of 23.15 meters and a transversal length of 8 meters and it was formed by a girder system of pre-stressed concrete containing 10 prefabricated double T cross section beams of 0.90m of height and two prefabricated U cross section beams of 0.96m height located on the edges. This beams contained variable quantity of strands (seven wired) in its top/bottom cross section and were connected thanks to a cast in situ deck of 0.14m on top. With respect to the pier cap it was formed by a transversal beams cast in situ made of pre-stressed concrete. The position and cross section of the elements can be seen in the next figures:
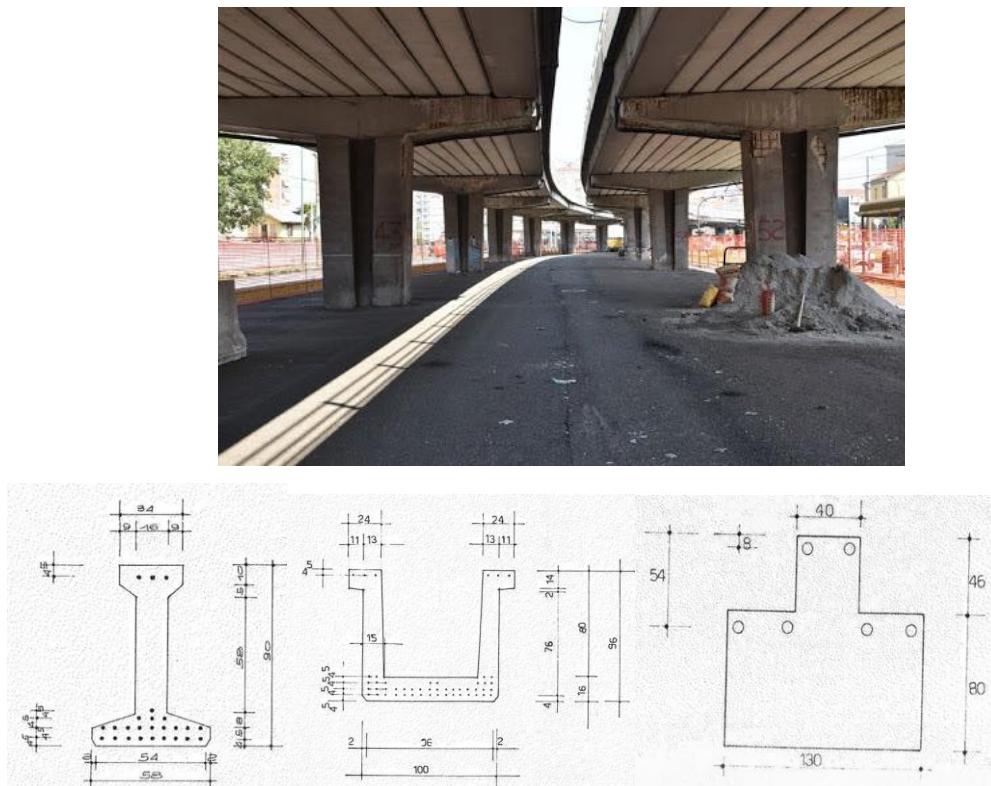
Figure 13. Position and Cross sections of the double T beam, U beam and cross beam from pier cap from design.

With the purpose of building a new underground pass and considering that the overpass had already fulfilled its life cycle, the bridge was demolished on 2019. However, in order to identify and characterize the damage present on the bridge at the end of its lifetime, the structural elements previously described were carefully dismantled and left to the Politecnico the Torino to study.

Thanks to this collaboration between Politecnico di Torino and the constructor company, twenty-five double T cross-section beams, four U cross-section external beams from

two different spans of the superstructure and two transversal beams from two different the pier caps could be analyzed in order to characterize its damage.

Figure 14. Beams in its state as dismantled.

The present work starts from a base where a structural health analysis of the present damage of each one of the elements in possession of the Politecncio di Torino has already been started. The damage on the elements has been characterized and schematized by a PDF document containing the following information:

- A picture from each face of the element.
- An AutoCAD drawing of each face of the element remarking its present damage (cracks, delamination, spalling or corrosion).
- Single pictures of most relevant damage present.
- A drawing of each one of the existing cracks for each face indicating its origin.
- A table indicating a progressive for the length and aperture of each crack.

As useful as this document can be for SHM purposes, it still has the limitations of a 2D document compared to a building information model. On the first hand, the document does not allow visualizing a 3D element, so the information about the damage needs to be subdivided into each 2D faces and a global representation is not obtained. Then, another limitation of the 2D document is that the interpretation of the data is not as simple as it can be done in a BIM model, as the information is separated into images, drawings and tables. Finally, a remarkable restriction of the 2D document is the inability to monitor changes of the damage on time. The quantity and differentiation of the information in the 2D document does not allow a simple integral modification or actualization of the data as it can be done in a BIM model.

An example of the PDF documents already created is displayed in the following page:
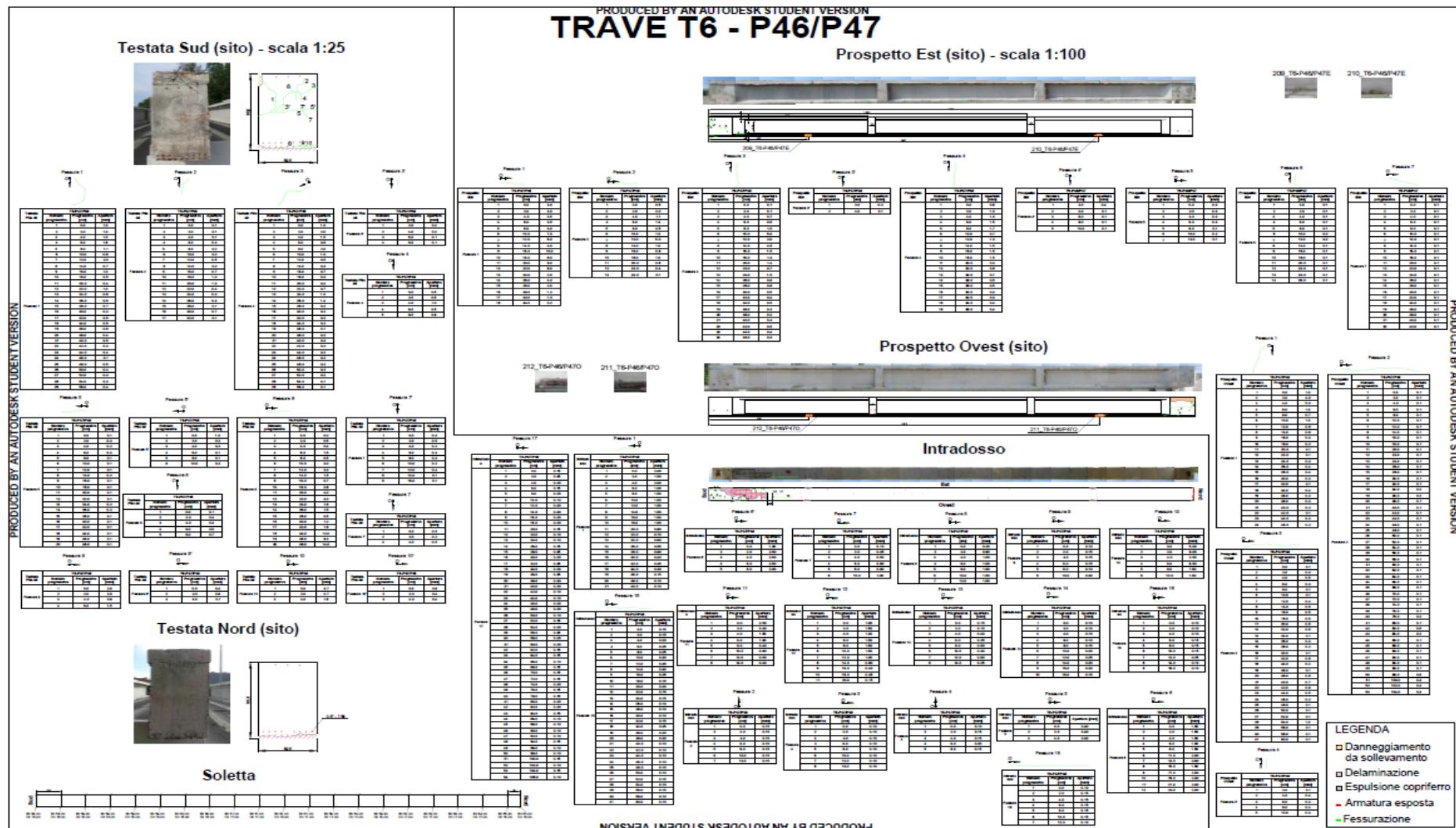
Figure 15. Previous damage characterization realized.

3.2.2   Stura River Bridge – Motorway connection RA10

The motorway connection RA10 is the connection road that allows the communication between the city of Turin and the international airport Caselle. This 10.7 km motorway is composed by a double carriageway separated by a central "New Jersey" barrier system with a double lane on each direction of travel. The road is also complemented with a flexible barrier system on the lateral sections. As this is a motorway type of road, the monitoring and maintenance procedures are in charge of the government owned company, ANAS. Approximately, on the progressive K2+800m form the start of the road in the direction Torino – Caselle airport, the Stura Bridge is crossed thanks to a 150 meters length double bridge.
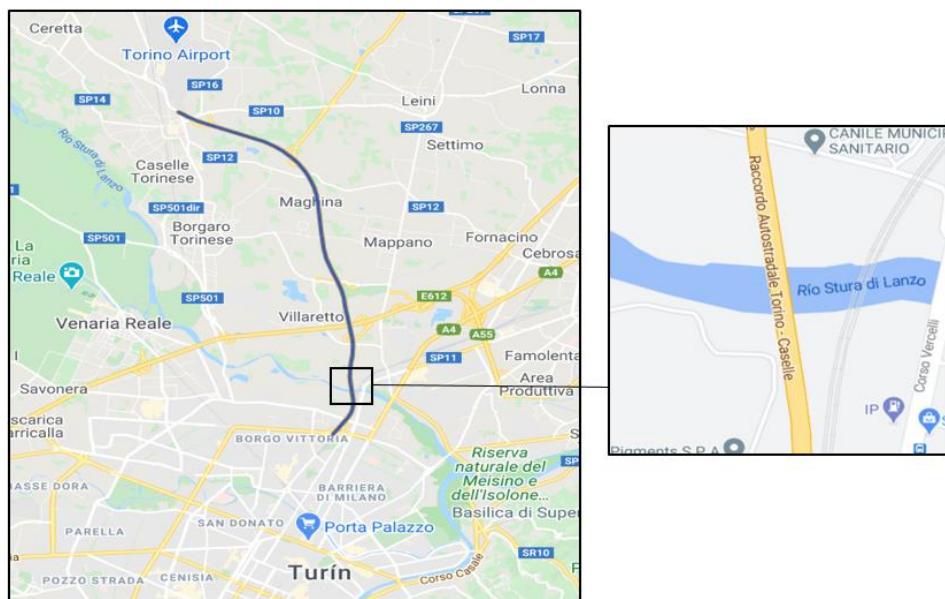
Figure 16. Location of the Stura Bridge on the RA10 connection motorway.

The Stura Bridge consist on two separated structures one next to the other, each one of them corresponding to a direction of travel. Each structure has five spans of variable lengths formed by a three main pre-stressed concrete girder beams system and complemented with squared sections transversal beams. On the superstructure, the bridge presents the same cross-section typology as the rest of the motorway (One structure for each carriageway containing a double lane) except for the barrier system, which is this case presents an H category steel parapet according to the normativity.

Figure 17. Stura Bridge on the RA10 from an aerial and a bottom view.

Due to the strategic importance of the bridge for the city of Turin and the high traffic that it experiences (Approximately 3500 vehicles/hour during peak hours according to a statistical survey report of traffic made in 2011 by ANAS) it has been subject of different monitoring activities during its lifetime. One of the most recent ones consisted on the collaboration work between ANAS and a private company (SYSDEV) for the installation of nine wireless multi-sensors on the bridge piers in 2018. These sensors allow the measurement in real time of deformations, displacements, inclinations and temperature. The data recovered by the sensors is automatically sent to a software for the structural modelation and actualization of information about the bridge.

Figure 18. Location of the sensors previously position on the Stura Bridge and the model created. Source: ANAS S.p.A. and SYSDEV – Monitoraggio struttrale di ponti e viadotti.

Considering this high amount of information present about this bridge this researched aimed to complete the model but this time following a remote sensing survey approach for its later importation into BIM software and a SHM inspection following the new Italian guidelines.

Originally, the idea was to survey the complete bridge, however, due to safety restrictions near the right bank of the Stura River and to the implementation of a novelty procedure to realize the photogrammetric survey with unmanned aerial vehicle (UAV) it was decided that on this work only the first span of the bridge was going to be analyzed.
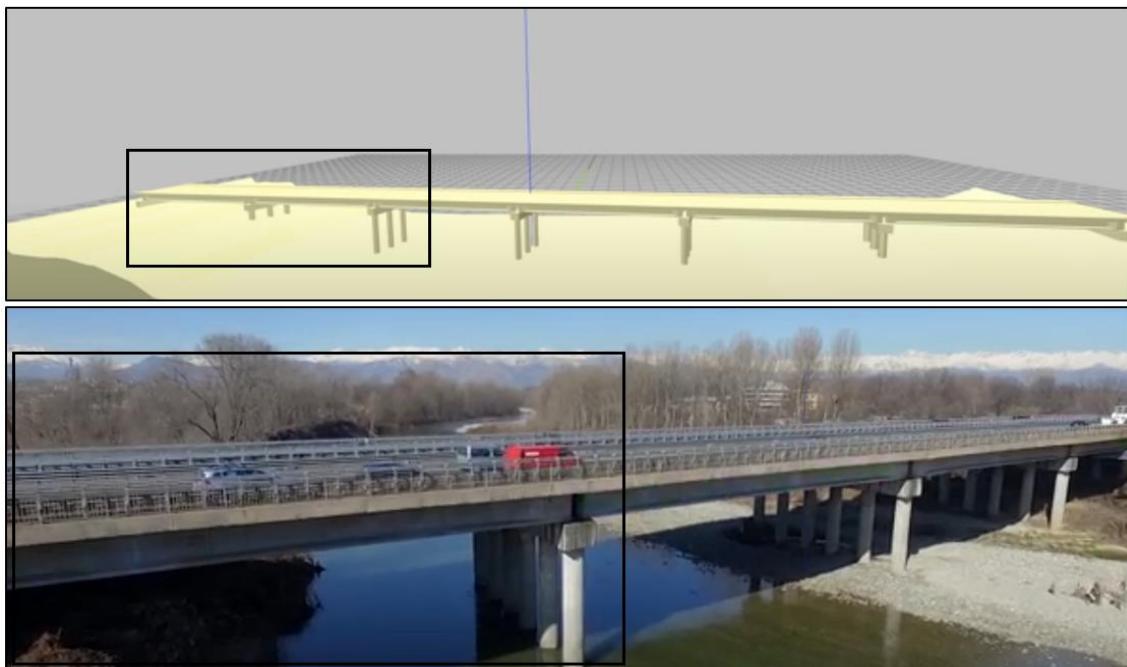
Figure 19. Spans of the bridge analyzed.

3.3 BIM Software used

- Autodesk Revit

Autodesk Revit is a BIM software that allows designing building and structures and its components in 3D and adding all the information needed to the project so a unique database can be created. As a BIM software, it allows a multi-dimensional approach, meaning that different stakeholders of the team can work on different areas of the project simultaneously and coordinated. As previously said the model created can be as detailed as needed, always taking into account that the level of development should be the minimum in order to satisfy the project goals. Taking as a reference the UNI11337-4 the level of development (LOD) is divided into two: level of graphical details (LoG) and level of information (LoI). For HBIM the correct LoG corresponds to level G, which indicates an up-to-date model with complete definition of elements and capability to generate renders. With respect to the LoI a L350 was considered appropriate as it considers information about materials, structural function, age of construction, interventions made, and model details about elements interference and relationships in between the system.

The software interface is subdivided in different elements considering its nature. The following table can be used to understand this environment organization:

Table 4. Revit environment classification system

	Description	*Example*
Category	Controls the organization, visibility, graphical representation and scheduling of the element.	Doors
Family	Defines parametric, graphical and documentation requirements of subdivided 2D or 3d information.	- Main entrance door - Elevator door . .
Type	A specific representation inside a family defined by distinct parameters and characteristics.	- 36´´ x 84´´ Flush - 36´´ x 84´´ panel . .
Instance	Is the actual individual element set inside the project.	- 36´´ x 84´´ Flush (L=3m)

Additionally, as elements from the families category are editable, they can also be further subdivided depending on its functionality. They can be system families, (Pre-defined and totally controlled by Revit software), loadable families (Users created families for specific projects that can be downloaded from public sources and loaded into a new project) and In-place families (Unique families that are created inside the project).

- Autodesk Dynamo – Visual Programming

Dynamo is visual programming software for design purposes. There are two different versions of this software. Dynamo studio, which is an independent open software and Dynamo as an extension for Autodesk Revit. Considering the version that complements Revit, it allows the access of the Revit application-programming interface (API) in order to automatize and set a various amount of data in an easier way. Dynamo is based on Python programming language; however, as it is a visual-programming tool it does not require deep knowledge in programming. Instead, it functions graphically, so that the user only needs to connect "nodes" and "arrows" in order to create a workflow or algorithm.

The implementation of Dynamo programming in Revit produces several benefits in the project such as the speeding-up of repetitive processes that can be easily automatized and the expansion of capacities of Revit, allowing it to create new geometries and parameters in an easier way. Moreover, as it is an open- source software, many scripts and "nodes packages" can be downloaded from internet libraries and be used on different projects.

Dynamo visual programming works on the following way:

- *Nodes:* Are the main element of the software environment. Each node represents a specific task and have inputs and outputs, which need to be connected through arrows in order to create a workflow. Nodes can be originally present on Dynamo, downloadable (from nodes packages on the internet), or user created (using python language programming).
- *Arrows:* Are the connecting elements between nodes so that a workflow can be created. Arrows communicate inputs and outputs of nodes in between them, and creates the workflow. The organization of the arrows is essential as it provides the order in which the workflow is followed. Moreover, in order to correctly connect two

different nodes, its "output" and the "input" to be connected need to be of the same type.

- *Dynamo player:* Is an interface inside Revit that allows the user to run Dynamo scripts directly on Revit without needing to open the Dynamo interface. This interface displays a list of Dynamo scripts in a specified directory, along with the possibility for the user to run it and the status of each script after it is run.

- *Dynamo Packages and user community:* Dynamo packages are the downloadable packages of user-coded nodes that were created from different users and are published for the dynamo community. These packages helps to amplify Dynamo functionalities in between Revit. Some of the most important packages that are going to be used for this projects are:

  o *Data-Shapes:* Collection of nodes that allow the creation of user interfaces so that dynamo parameters can be edited by the user without the need of opening the programming tool.

  o *Mesh toolkit:* Collection of nodes that allow the importation of meshes from external file formats, create meshes from Revit geometries and in general mesh operations in Revit.

  o *Clockwork:* Collection of nodes for various purposes such as workflow management and control, geometric, strings and mathematical operations, lists operations, material and elements creation, etc.

  o *Archi-lab and Archi-lab Bumblee:* Collection of nodes for various purposes like list management and elements characterization. Provides also an important interoperability tool between Revit and Microsoft excel.
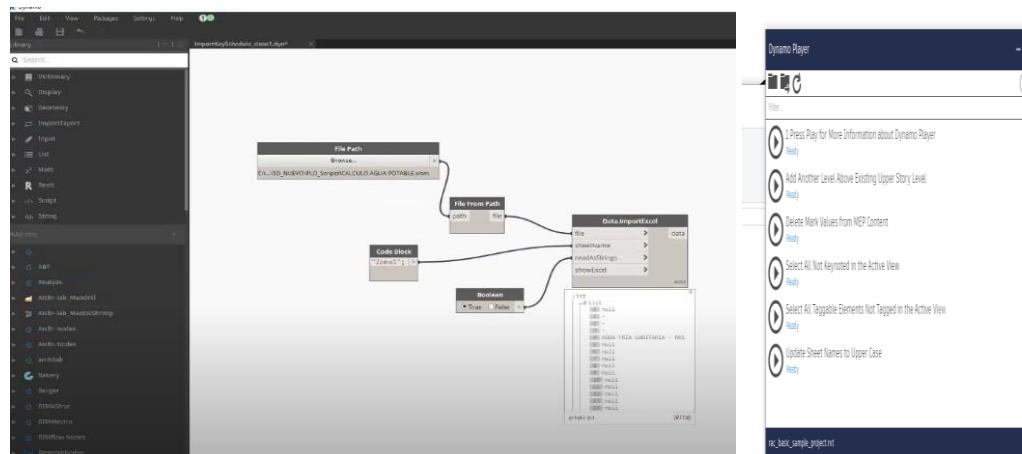
Figure 20. Dynamo and dynamo player environment.

3.4 Photogrammetry, Laser scanner and mesh editing software used

- Autodesk Recap Pro – Recap Photo

Autodesk Recap is a software that allows the creation of 3D models from reality capture data (Such as laser scanning and photogrammetry) and its further editing. Recap structure allows the importation of either a point cloud file or a set of images in order to create a triangulated 3D mesh (3D model). Depending on the type of data to be imported, different paths can be followed to process the information. If the data from the survey is a point cloud file it can be directly imported into Autodesk Recap in order to create the 3D model. On the other hand, if the survey data comes from a photogrammetry process may be imported using a software extension (that is automatically downloaded with Recap) called Recap Photo. From Recap Photo a dense point cloud can be also generated from the photographs. Specifically, Recap Photo allows the processing in "Object mode" which allow the uploading of a maximum of 300 photos using a limited Autodesk cloud space of 25 GB and the "Aerial mode" which allow the uploading of a maximum of 1000 photos using a limited Autodesk cloud space of 80 GB.

The software structure allows the user to break the data to be processed into manageable pieces of information so that a more workable model is generated. Moreover, when the 3D model is created the software allows the application of a set of filters that permit to set outer limits to the data, and create boundaries to eliminate "noise shots" that may have been picked up by the scan. Additionally, the software have some tools to clean up, view and modify the 3D triangulated mesh. These tools may result useful for a first editing of the 3D mesh; however, its functionalities are simplistic and does not allow a complete editing of the mesh.

The output of this software can be either a point cloud (.PLY/.FBX format) or a triangulated mesh (.OBJ/.STL/.SAT format). In the case of the point cloud information, this type of data can be directly imported into Revit. However, on the case of the 3D object (which is the output needed for this project) interoperability problems are presented as no direct importation from this software is possible.
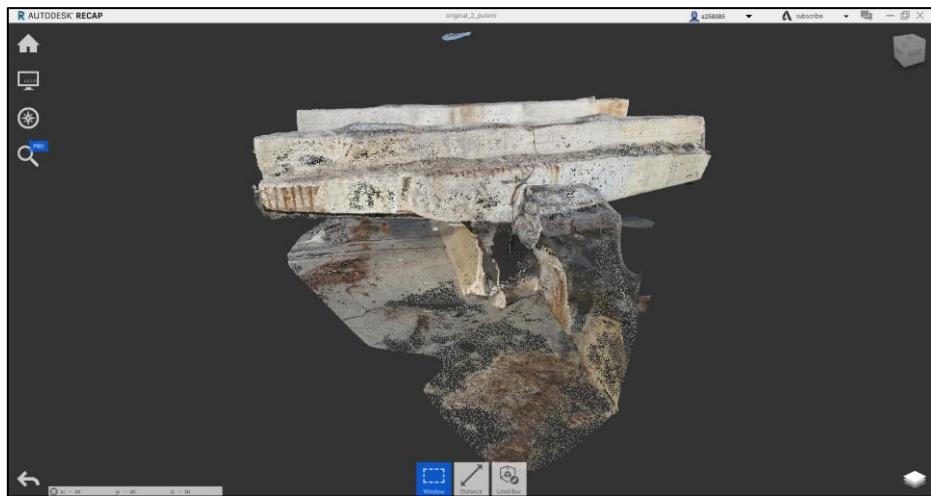
Figure 21. Autodesk Recap interface.

- AgiSoft MetaShape

Agisoft MetsShape is a software dedicated to perform photogrammetric processing of digital images and generating 3D spatial data such as point clouds, meshes, textures, Ortho-photos, digital elevation models, etc. that can be used in to be GIS context. The software allows the importation of any of the previously mentioned products; however, in order to create a model from photographs a photogrammetric survey, a simple workflow must be followed. Initially, the images from the survey need to be imported and aligned. The number of photos that can be processed by the software depend on the RAM characteristics of the equipment and the reconstruction parameters used. In order to provide an idea, assuming a single photo resolution of the order of 10 MPix, a 16 GB RAM will allow to process up to 300-400 photographs. Moreover, images from different cameras can be loaded in the same project taking into account different calibration settings (Camera type, focal length, radial distortion, etc.). On the other hand, alignment of the images means to position the cameras in the correct position in order to reconstruct a 3D point cloud. This process can be made automatically by the software taking into account the key point and tie points in the images (Easily recognizable common points between image pairs). From this process, a sparse point cloud model is obtained. In order to provide the correct scaling and georeferenciate the model obtained the software offers several type of options. If the camera used to obtain the images contains a GPS, the coordinates of the position from where the image was taken can also be obtained. Moreover, on this step it is also possible to import ground control points

coordinates from a text file (Points that have a known coordinate from the survey process) and place markers (recognizable equal points in two different images).

From the spare point cloud, the dense point cloud can be obtained in order to produce a highly dense 3D reconstruction of the surveyed subject. Different parameters can be set for this task taking into account the relationship between quality of the model vs computational time required for the model creation. After the dense point cloud is created, a set of filters can be applied to limits and decimate the data, and create boundaries to 3D cloud.

Other options in the software allow also the creation of a polygonal mesh based on the cloud information, the creation of the texture for the created mesh, the creation of a digital elevation model (DEM) and obtaining orthophotos of the created model.

The dense point cloud as well as the triangulated mesh obtained as an output on this software can be exported in several format types (.PTS/.PLY/.OBJ/.FBX etc.). However, as it occurs from the output of Recap, the point cloud data can be directly imported into Revit but for the importation of the 3D object, obtained interoperability problems arise.
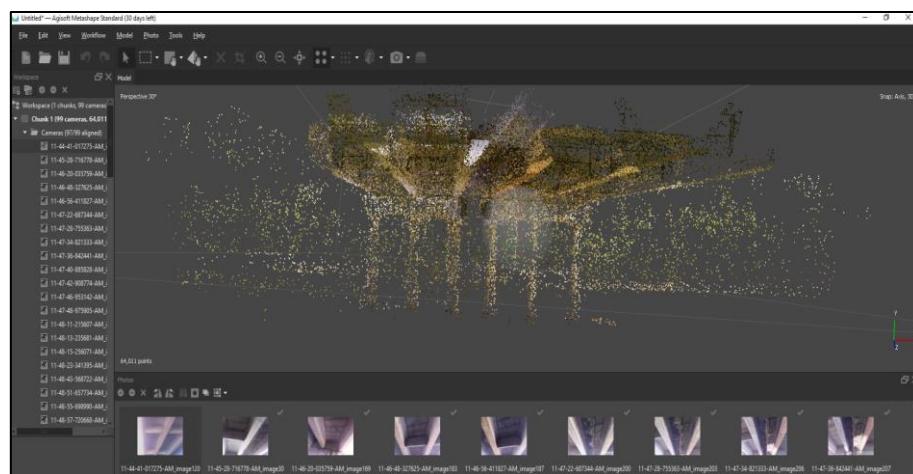
Figure 22. Agisoft Metashape interface.

- Faro Scene

Faro scene is a software developed by the company Faro Technologies, which specializes on producing remote sensing systems such as LiDAR. With this type of software, scan data taken on-site or from terrestrial devices from can be processed and managed. On this sense, this software is useful to process all the information obtained

from laser scanners. The software uses on-site registration, automatic object recognition, scan registration and target-based scan positioning to create 3D point clouds. Data from different scans can be uploaded into a single project to obtain a unique complete 3D output. The produce this 3D point cloud pre-processing and processing operations are needed. These operations can be made varying different filters and parameters in order to obtain the best quality of the model. The RGB information from images can also be applied to the scans if the laser scan used for the survey contained a camera. From the pre-processing parameters, the artificial markers placed during the survey can be automatically recognized and the text file containing the coordinates of the points can be included so that the model can be geo-referenciated. If no artificial markers are placed during the survey, the software can still create the model in a similar way as the software PhotoScan does, identifying key point and tie points in the scans. After this process is done, the scans are set into their correct position to generate the 3D point cloud. The quality of the positioning can be determined during this processing step.

The processing of the scans refers to the creation of the final 3D point cloud from the scans. Different options are also available for this operation such as deleting repeating points or homogenize the quantity of points. When the final 3D point cloud is obtained, different filters are available in order to divide, section, and create boundaries to the data obtained. Additionally, this software also allows the creation of the triangulated mesh, however, the quality of this one is not as good as the one obtained from other specialized software, as this is not its main scope.
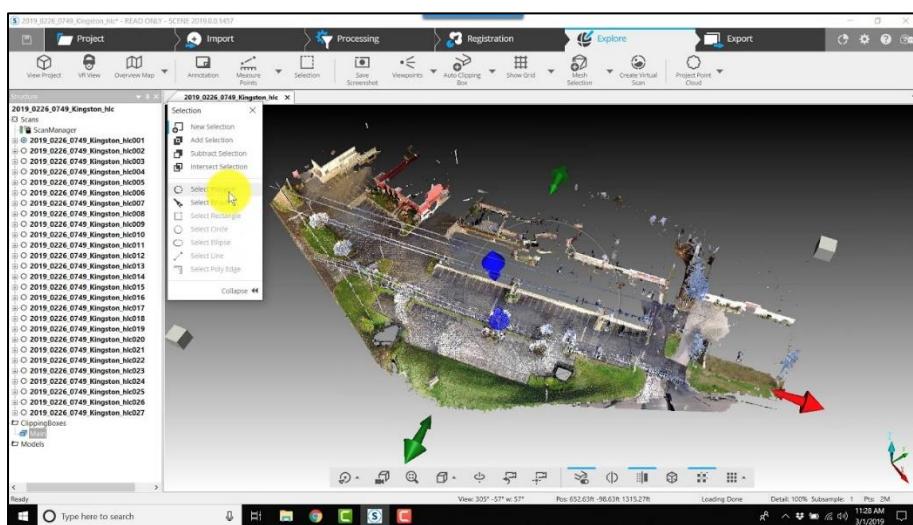
Figure 23. Faro Scene interface.

- MeshLab

MeshLab is a free, open source software for creating, processing and editing 3D triangular meshes. This software provides several set of tools for editing, cleaning, optimizing, inspecting, texturing and processing the 3D meshes. This software is particularly useful because it allows an easier and efficient approach to more technical tools for 3D development and data handling.

Some of the more useful tool groups in MeshLab software are the following ones:

- Normal, curvatures, orientation filters: This group of filters allow the computation of normal from a 3D point cloud in order to generate a triangular mesh. These filters captures groups of points, creates planes and use these planes to calculate normal.

- Mesh surface reconstruction filters: This group of filters provide different algorithms in order to create meshes from a 3d point cloud with normal already generated. This is the key filter in the mesh creation process as the algorithm and its parameters determine the quality of the mesh obtained. Different algorithms for this task are provided such as the Ball pivoting algorithm and the VCG (Variant of the cureless); however, the most used one is the Poisson surface reconstruction. This filter consider all the points at once to create the triangulated mesh without spatial partitioning or blending, therefore unfortunately it is to highly sensitive to data noise.

- Mesh Cleaning filters: Allow the automatically removal of duplicated or unreferenced vertices, the deletion of null/non manifold faces, the elimination of small isolated components and the automatic filling of holes, in between others.

- Remeshing filters: Allow the high quality compression, set into scale and simplification of the mesh through different possible techniques, as well as the surface smoothing, hardening, subdivision or reconstruction.

- Colorization/Inspection filters: Allows the colorization, selection and division of the mesh through a vast quantity of parameters such as border edges, normal to x, y or z plane or by size.

- Selection/deletion/coloring tools: Allows the easy selection of any portion of the mesh and its efficient editing, deleting, coloring, subdivision, layering, etc.

- <u>3D scanning tools</u>: Allows the alignment and merging of different 3D meshes into a simple model or the joining of texture information with 3D object information through a parametrization process.

Additionally, MeshLab present an enormous advantage, which is that, allows the exportation of the data in a vast type of formats, including in between them AutoCAD format (.DXF) which can be directly imported into Revit.
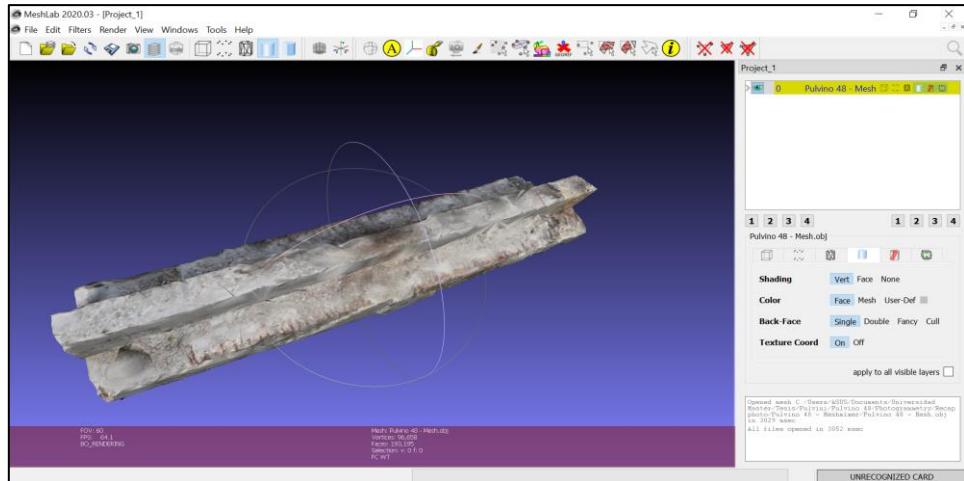
Figure 24. MeshLab software environment.

3.5 Methodology and workflow

- <u>Largo Grosseto Overpass</u>

Considering that the damage information on this case was already summarized, it is logical that the first task to realize in this work is to pass the information from the 2D documents into a BIM model. The information of the previously made work was summed up in AutoCAD, no interoperability problems were expected in its passage to Autodesk Revit. Of course, as this project refers to an As-is model, all the families were the information was imported were In-place families.

For the structural elements, two procedures of modeling were followed taking into account that not all beams counted with the same input information. The parametric modeling option was used for the beams in which no photographic survey was available: Double T and C cross-section beams. For these beams, the measurements from then PDF documents and the drawings from the AutoCAD files were used in order to determine the geometry of the elements and a set of parameters was created to control these measurements.

On the other hand, for the Pier caps a photogrammetric record was available so a photogrammetric work was done to represent the real shape, measurements and textures of the element.

This process of modeling started by selecting the correct photos in order to create the model. After the correct photographs were selected, the software Autodesk Recap Pro an Autodesk Recap photo were used to create the dense point cloud and the 3D objects. Different models were created considering for each one of them different number of pictures in order to compare the models quality against its size and computational demand. Once the correct model was chosen, a first optimization of the mesh was made on this software, eliminating some of the digital noise that was present on the model.

The interoperability problems between software started arising on this point, while many different exportation formats of this software (.OBJ/.FBX/.PLY/.STL/.SAT) were tried for the direct importation of the 3D mesh to Revit, but unfortunately, none of them allowed its accomplishment. Two different options were found in order to allow a semi-direct importation process was followed of the triangulated mesh to Revit:

- The usage of the package *Mesh toolkit* from Autodesk Dynamo to import meshes into Revit in the format .OBJ/ .FBX/.SAT
- The usage of the format .DXF to export the mesh into CAD format

Nonetheless, the fact that Revit is not a software dedicated for dense point cloud operations and 3D mesh editing is noted on the computational time required for this passage of information and the loss of information during the importation process.

With the first solution found for this procedure, the usage of *Mesh toolkit*, the importation time took a long time and the operability of the mesh imported to Revit was almost zero. Simple tasks such as orbit in Revit to see the mesh took long time and make the software close unexpectedly. The only way that the meshes imported with this methodology could be used inside Revit required a profoundly decimated mesh (less than 10,000 faces) which made the quality of the geometry be extremely inaccurate. Moreover, in none of the three formats allowed with this methodology (.OBJ/ .FBX/.SAT) the texture is recovered, so a no-colored model results in all cases.

With the second solution, the usage of the .DXF format to import the mesh, a more defined mesh (meshes of up to 550,000 faces were imported into Revit without operability

problems) can be imported into Revit without losing the operability of the software. However, on this case also the texture information is lost, so a no-colored model results.

Taking into account that the second options allows the importation of a more defined mesh the .DXF format of the mesh was used to take the 3D object into Revit. In order to do this the mesh needed to be exported firstly into MeshLab, re-optimized and exported into the correct format to pass it to Revit. Then, to color the model again, the model needed to be previously divided into layers according to its planar faces so that frontal images from photographs could be set as material texture.

The 3D mesh of the beams obtained on Recap photo was exported in .OBJ format and imported into MeshLab. On this software the 3D mesh was set into the correct orientation and scale (As it was not georeferenced during the photogrammetric survey), the extra digital noise was eliminated, the present voids were filled, the mesh was subdivided into different layers and an optimization and compression process was applied to make the mesh workable on BIM software. This last step is key in the quality of the final obtained mesh, because the compression of the mesh implies a reduction in the number of vertex and faces in order to make it workable in CAD/BIM software but also implies a reduction in the quality of the final obtained 3D object. Unfortunately, as photogrammetry creates a "disordered" point cloud, irregular polygonal meshes are obtained so a reduction of vertex on areas where more small sizes triangles are located does not imply a significant change, but on areas where less and bigger triangles where are located the change may be noticeable.

The passage of the 3D mesh into MeshLab is necessary not only for its utility for mesh operations, but also because it allows the subdivision of the mesh into different layers and its exportation into the .DXF format, passage that was impossible using other photogrammetry software.

Lastly, using the .DXF format, the final importation to Revit was made and the model was ready to be colored once again. Before the frontal images (Obtained either from orthophotos in MeshLab or from Real frontal pictures taken on site) were put into the model as texture, a photo editing process was made in Adobe Photoshop in order to eliminate background noise and set the correct dimensions to the picture. Finally, after the image-editing job was made the pictures were put as texture of the model in Revit, and the information from the damage and the structural model was joined.

With respect to the damage information on the beams, as it was already drawn in 2D in AutoCAD and the information about its depth and opening was listed in an excel table, a simple importation was needed from AutoCAD to the Revit family, and according to the information on the excel tables the 3D shape was given to the damage. Then all the information corresponding to the damage characteristics and additional notes from Excel, photographs, and PDF documents was put as parameters of damage information.

The final step was proving the application of the model with a temporal scale and the annotation of the model in order to indicate the damage from a global perspective view. For the first task, additional "dummy" damage was created on different time scales and the phasing possibility given by Revit was used in order to visualize damage from new possible inspections in the future, without losing the information from past revisions. On the other hand, for the annotation of the model from a global perspective, a new family of 3D labels was created and added to the model, to indicate from a global perspective where the damage is located and how severe it is to the structure.

- <u>Stura River Bridge – Motorway connection RA10</u>

Considering that for the Stura Bridge no damage information was already recovered and no survey of any type was realized previously, for this study case no parametric families needed to be created and no passage of information of the damage was needed. Instead, this study case started with the complete survey of the first span of the bridge in order to create the 3D model and then the passage of the model into the BIM software, Revit. Once on Revit, this first span modeled with a remote sensing approach was joined with a parametric model of the bridge created for a previous thesis work, in order to notice the difference on the two approaches and have a complete model of the bridge. Moreover, on Revit, a user interface was created using Dynamo visual programming in order to apply the level 0 and level 1 of the new Italian guidelines directly into the BIM model.

On this sense, this work started with the complete site inspection and survey and of the first span of the bridge on site. This survey was possible thanks to a collaboration process with the Geomatics Team of Politecnico di Torino. The first step on this task consisted on the creation of a topographic framework through the usage of GPS/GNSS and ground control points. This procedure was performed positioning markers in different positions of the bridge and then using a total station to determine their coordinates. Then, different laser scanner surveys were performed using the instrument FARO CAM 2 and

a terrestrial photogrammetric work was completed. Moreover, a completely new type of photogrammetric work was done in order to complement the model created. This photogrammetric survey was performed using an UAV, with the novelty that on this case the camera was positioned looking upwards with an angle of 45 degrees, instead of looking downwards as it traditionally is located.

After the survey was completed, the processing of the data obtained started. This processing may be divided into three big areas taking into account the type of data to be processed:

- Processing of the data from the GPS/GNSS software with the software Microsurvey StarNet to obtain the topographic Network.
- Processing of the data from the laser scanner in the software Faro Scene, geo-referencing the scans with the topographic network data and creation of the 3D point cloud.
- Processing of the data photographs from the UAV in the software Agisoft MetaShape, geo-referencing the photos with the topographic network data and creation of the 3D point cloud and the triangulated mesh.

After the two point clouds were created, they were uploaded in MeshLab in order to join them together and apply the same mesh operations as in the previous study case. Once the meshes were ready, the .DXF format was used once again so that the model was imported into Revit. Again, on this case the texture information was lost while passing the model into this format, so texture from images was put back as materials in Revit.

Once on Revit, the complementary software Autodesk Dynamo was used in order to create a user interface so that the damage inspector can directly apply the level 0 and level 1 of the new Italian guidelines directly on the software. This was made creating several damage families (no geometry but only information) corresponding to all the information contained on the guidelines, and a user interface, so that the technician on charge adds the information that may consider necessary and fill its parameter. Finally, a new script was created so that once the technician has finished the inspection of the model all the information can be exported into excel sheets, as the guidelines require.

The complete process made for both study cases on this thesis can be summarized with the following workflow:

Workflow Largo Grosseto Overpass
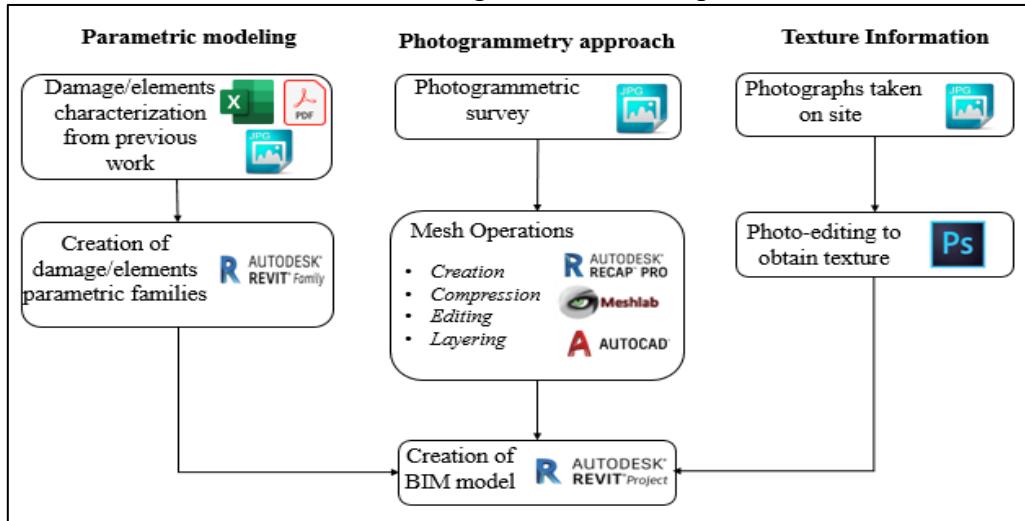
Workflow Stura Bridge
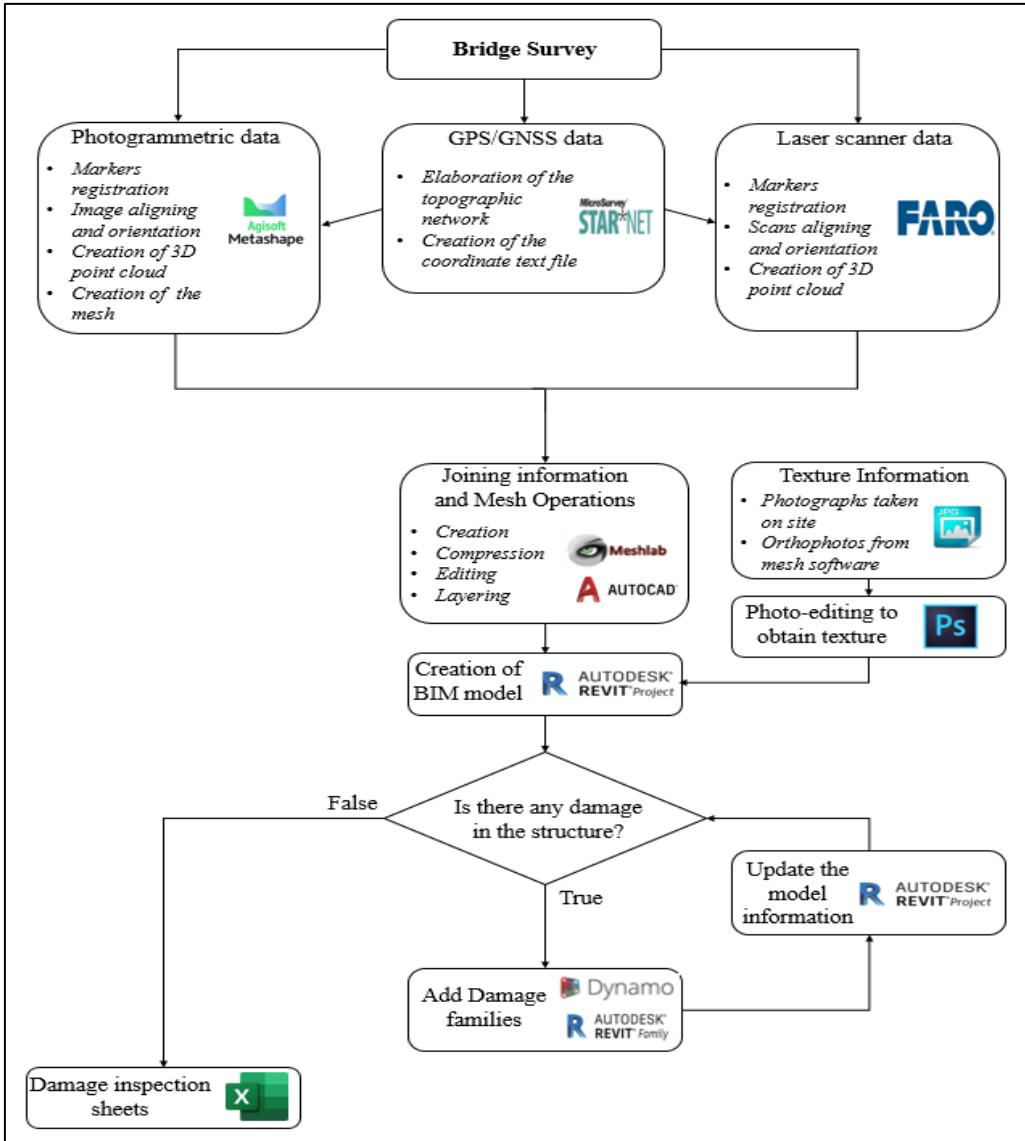
Figure 25. Workflows of methodology used.

Chapter 4: Work development

4.1 Largo Grosseto Overpass

4.1.1   Elaboration of Revit model - Beams parametric families

A new Revit family project was created for this task in order to create an In-place family. The category chosen for the structural elements it was decided to set the category *"Structural framing (beams)"* as it is the one that better fits according to Revit options. Then three different families were created according to the double T beam, U beam and cross beam from pier cap. Finally, they were further subdivided in Types considering its unique specific real geometries.

Table 5. Revit subdivision for beams families.
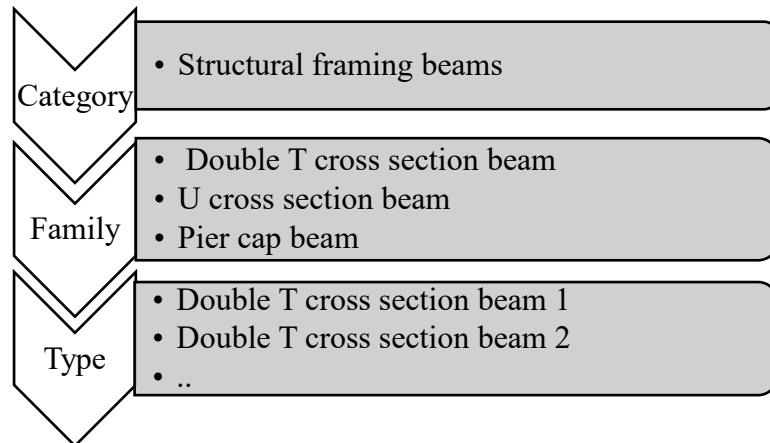
For all families a 3D geometry was created parametrically following the real in-site measures reported on the PDF document. A parametric geometry means that its shape can automatically change depending on values from parameters set as an input by the user. Hence, for each geometric detail on the beam a parameter was created.
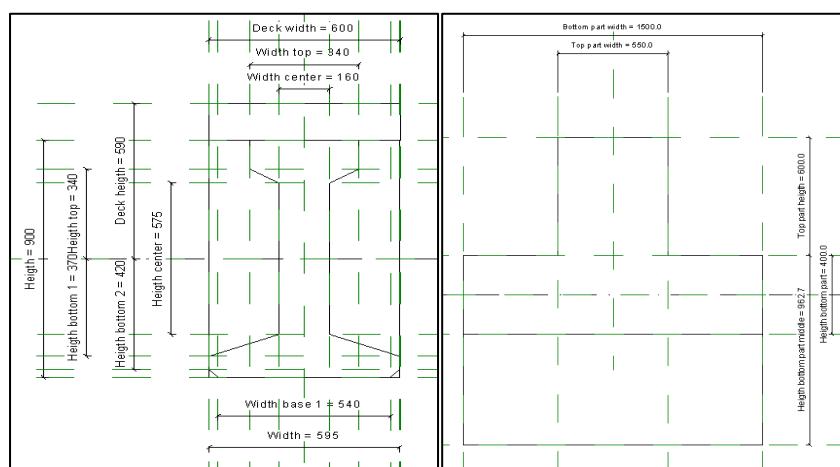
Figure 26. Parametric geometry of beams created on Revit.

Figure 27. Parametric family created on Revit for double T beam.
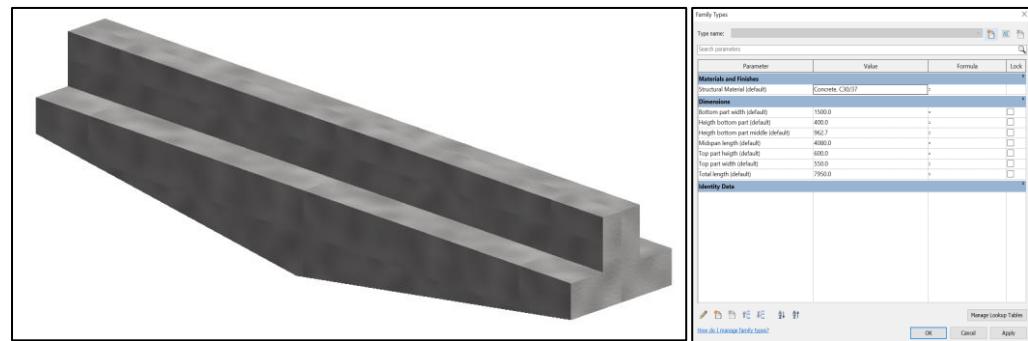
Figure 28. Parametric family created on Revit for beam on pier cap.

The fact that the measurement used for each beams are unique and come from a previous in-site survey allows a personalization according to reality of each beam. However, despite this personalization, with this method of modelation none of the details about imperfections or textures cannot be taken into the model, so some important information for the SHM process is lost.

4.1.2   Elaboration of Revit model - Damage family

With respect to the structural damage information, as there was no predefined category for "damage" in Revit, it was decided to use the category *"General model"* as it allows putting all the information needed in the model and creating a basic geometry according to the damage. Then different families were created according to the type of damage (Cracks, delamination, spalling, and corrosion) and the beam at which they belong. Finally, different types were created in order to define the specific damage characteristics and geometry.

Table 6. Revit subdivision for damage families.

Category	• Revit general model
Family	• Cracks • Delamination • Corrosion • Spalling
Type	• Crack 1 - Double T beam 1 • Crack 2 - Double T beam 1 • ..
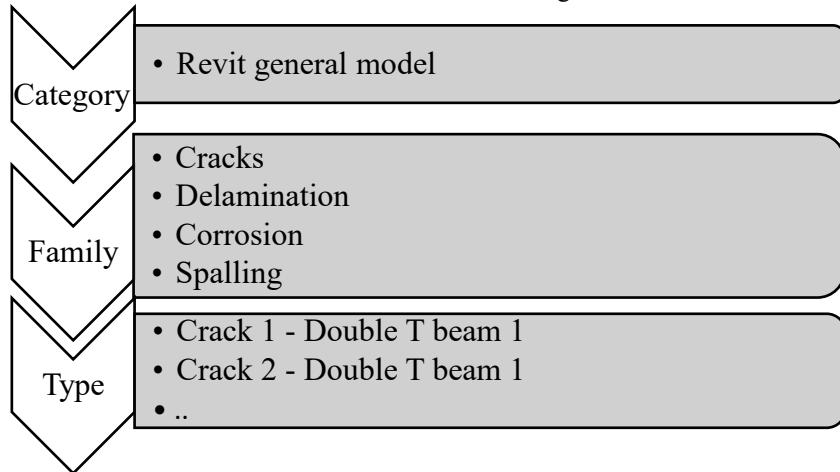
Then, to the Revit family template the AutoCAD drawings of the damages was imported using the *"Import CAD"* command, and the 3D geometry was created using the *"extrude"* tab and following the data from excel and PDF indicating the damage opening and damage depth.
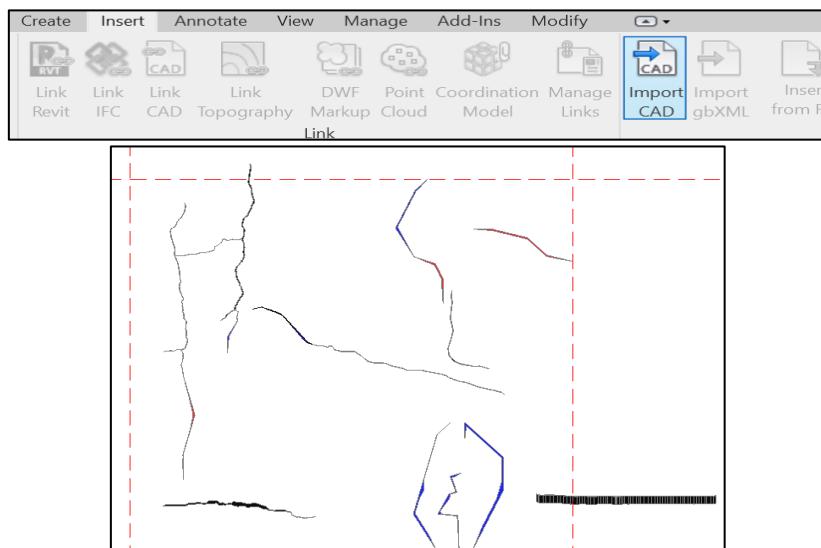
Figure 29. Import option on Revit and example of family of cracks created.

Then, the following information was added into the model taking into account the PDF and excel files made on the previous works:

- Data of modeling (Data)
- Operator ID (Text)
- Damage Type (Text)
- Damage ID (Number)
- Damage length (Dimensions – cm)
- Damage Depth (Dimensions – mm)

- Damage opening (Dimensions table)(Progressive (cm) – Opening (mm))

- Damage length (Dimensions – cm)

- Damage origin (Image)

- Note (Text)

With respect to the origin, a .JPG image of the damage indicating its origin was included.
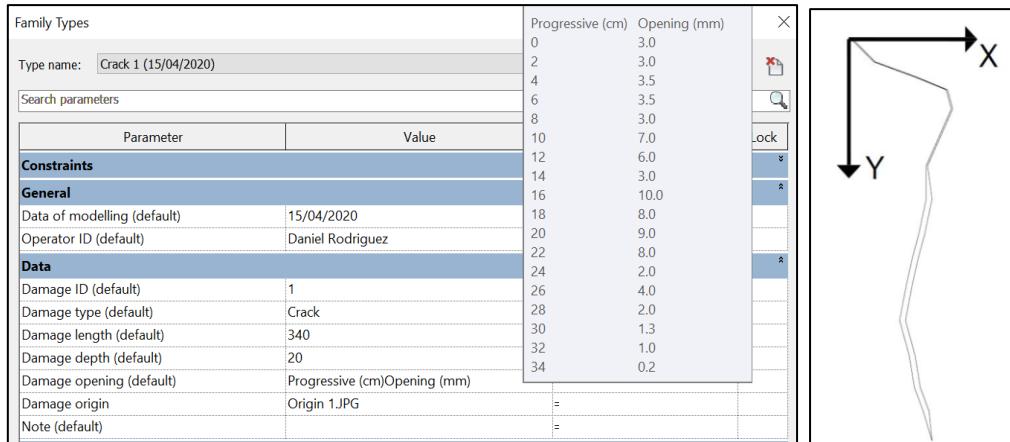
Figure 30. Information added to damage families.

4.1.3   Creation of Over-Time scale on BIM Software

Once the damage families were created it was needed to add a temporal scale to the model, so it can be modified and actualized according to the real changes that occurred on the beams. In order to do this, the *"phase"* filter was used on Revit. Each Revit project has a phasing section to control the visualization of the elements. This section was originally created in order to include in the project demolished, already existing or new constructed elements and differentiate its visualization. However, in this case this section results extremely useful as it allows controlling the visualization of different damage according to a parameter of choosing, on this case the "*data of modeling*" parameter.

In order to demonstrate the utility of this phase filter, some fictional "dummy" (not existing) damage was created and assigned a different parameter *"Data of modeling"* so that it can be displayed only when changing the *"phase"* on the project. This "dummy" damage created included not only new damage but also different enlargements or modifications of the existing reported damage, representing normal situations that may happen on the reality. To these new damage red and blue color was assigned through the

"material" option according to its data of modeling in order to correctly detect it as the phase was changed.

After this process was made, the damage family was joined and correctly positioned in a Revit Project template with the parametric beams families. The final step to complete the model was the creation 3D sphere label family in order to locate the damage in the model from a perspective 3D view. These labels contain the same information as the damage that they represent, so from a global point of view the user can identify the most damaged areas on the beam and get the information of the damage characteristics. Different colors and radii were assigned to the labels corresponding to the damage severity and extension respectively.
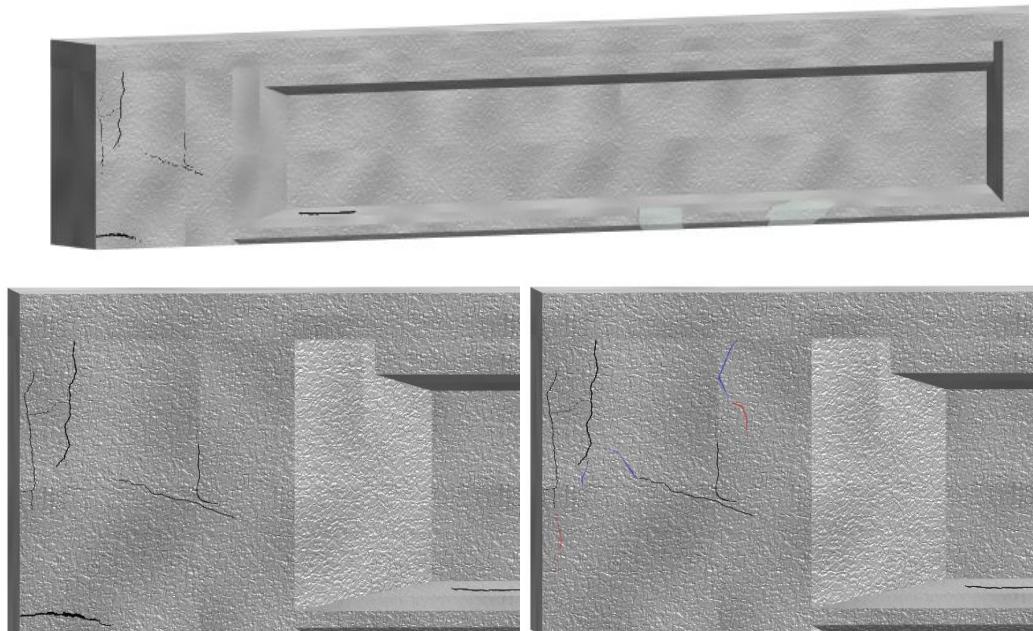
Figure 31. Example of damage and beam family joined on two different phases.

Figure 32. 3D Label system created.

4.1.4   Elaboration of Photogrammetric model

Taking into account that this part of research took place while the coronavirus pandemic reached peak in Italy and that outdoor work was limited by mobility restrictions, on this phase of the research only the photographs from the beams of the pier cap were available for the photogrammetric model and no topographic survey was available to geo-referenciate these photographs.

In total 86 photographs from different angles of the two-pier cap beams were available to create the 3D model. Unfortunately, due to the difficulty to detect all of the angles of the beams in the photographic survey done, some voids remained on the model, especially in the intrados of the beams. In order to create the 3D geometry the software Recap photo was used.

Taking into account that this software on its educational version provides a limited Autodesk cloud space of 25GB that were required to last for all the different models that needed to be created, an analysis in terms of computational time vs model definition was done. Different models of the same beams were created using 50, 70 and all 86 photos for its evaluation. Of course, the pictures selected to create the models were carefully selected in order to show in a complete mode the beams to be represented. The results in terms of quality of the model, computational time required and cloud space required are summarized in the following table:

Table 7. Comparison of 3D Models using different number of photos on Recap Photo.

Computer characteristics	Number of photos used	Computational time required	Cloud space required	Model quality
Intel core i5 with 8GB ram and 512GB SSD	50	2:45 hours	21.5 GB	Acceptable quality model. Some lack of information and details
	70	3:15 hours	22.1 GB	Intermediate quality model, with some lack of information and details
	86	3:50 hours	23.3 GB	Best possible quality model

Figure 33. Models created with 50, 70 and 86 photographs respectively.

From this evaluation, it can be seen that as expected the model realized with the more pictures have the better quality, but at the same time occupies the greater space and demands more time for processing. On this research, it was decided to work with the most detailed model (On this case using 86 photographs) considering the following arguments:

- For SHM purposes, the model should be as detailed as possible in order to detect damage of milimetric scale.
- The model will be compressed in further steps to ensure its manageability on BIM software, so a certain loose of quality will eventually occur.
- The difference in required cloud space is not as big as it can be initially expected (28% an 15% with the model of 50 photos and 70 photos respectively).
- The difference in required computational time is not as big as it can be initially expected (7% an 3% with the model of 50 photos and 70 photos respectively).

Then with the correct model chosen, operations of resizing according to the correct scale, cleaning the present digital noise, optimization, compression and exportation of the 3D triangular mesh to BIM software needed to be done. For these tasks, Recap Photo presents some useful tools like "*Slice and fill", "Decimate mesh"* and *"smooth boundaries"*. However as the main use of this software is the triangulated mesh and texture creation and not its editing, after some attempts of using these tools they were

found rather complicated and with problems of precision. The only tool used for mesh editing on this software was the "*slice*" tool in order to eliminate some of the digital noise present and set the model initial boundaries.

As previously mentioned, Recap only presented possibilities of exportation as 3D objects (.OBJ/.FBX/.STL/.PLY) or as 3D dense point cloud (/.PTS). As there is zero interoperability with 3D object and BIM software, none of these initial formats can be of use on this object. With respect to the dense point cloud format, it can be imported into BIM software, but it cannot be used for direct modeling, but only for its overlapping with a parametric model already created and comparison. Nonetheless, the /.PTS format was used to export the model as dense point cloud, in order to compare the original point cloud obtained with the one of the compressed model.

From the original models, the following information could be obtained:

Table 8. Original mesh and point clouds details.

Autodesk Recap photo – 3D triangulated mesh		Autodesk Recap Pro – 3D dense point cloud	
Number of vertices	2.513.827	Number of points	4.48 million
Number of vertices	4.665.135	Limit box distances	19.137m x 20.897 m
Surface area	1.733 m^2	Elevations	From -4m to 11m (14.365 m)
Surface Volume	1.360,870 m^3	Model size	178.576 KB
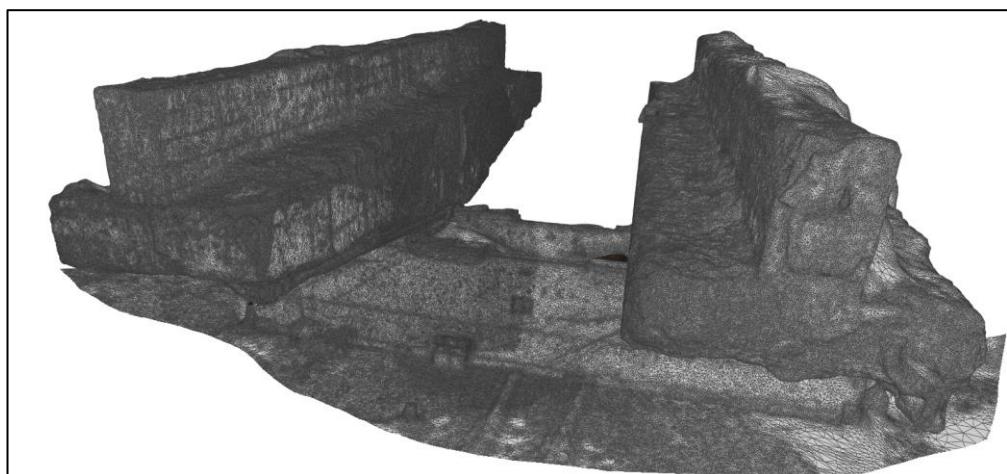
Figure 34. Details of original 3D mesh obtained (without texture).

Figure 35. Details of original point cloud obtained.

Then, in order to realize the 3D triangulated mesh operations to obtain the correct 3D object for an importation to BIM software, the original model was exported from Recap Photo as 3D texturized object in .OBJ format and imported into MeshLab.

4.1.5   Triangulated mesh operations

Once the triangulated mesh was imported into MeshLab, separation of elements, operations of cleaning the present digital noise, setting into scale, repairing, layering and compression were applied.

The first operation done was setting on the correct orientation and scale factor. For this task, the *"measurement"* and *"Transform scale"* tools were used. As no topographic survey was realized, the original model created does not include any information about the scale factor or unit of measurement, so these parameters are arbitrary selected and does not represent the same as the one from the real world. In order to determine the correct scale factor, the ratio between the measurement from the in-site survey and the corresponding measure obtained with the *"measurement"* tool in the model needs to be applied to enlarge or reduce the model. The *"measurement"* tool on MeshLab produces and Euclidian measurement on the model (the shortest distance between two selected points), so a planar surface should be selected on site so it can be compared with the one on the model. Moreover, the more measurements available from the on-site survey, the better the scale fitting can be. In this case, measurements from the beams were already present on the PDF from previous steps, so a several number of data was available in order to set the correct scale factor. Additionally, the *"Transform scale"* tool allows to set a different scale factor on the X, Y or Z plane, however, as the distances

between points is consistent independently of the plane of measurement, a uniform scaling, origin-centered with a value of 0.3462 was applied.

The second operation done on the model was the separation of elements, the elimination of digital noise and the fixing of problematic details. For this task, the *"select"* and *"delete"* and "*Fill holes*" tools were used. On this case, as the model included the two pier-cap beams, it was split into two models, each one of them for one pier-cap, to work independently on each one. In order to apply the first two tools, a manual work is performed by selecting all of the extra elements that should not be present on the model and cancelling them. With respect to the "*Fill holes*" tool, the software automatically detects and selects all open voids in the model of higher value than a value selected by the user and fills them with a new face without texture. In this case all voids greater than 0.01m were selected and filled in order to have a completely closed mesh. As the model did not present any big void, so no blank spaces in the model texture were created.
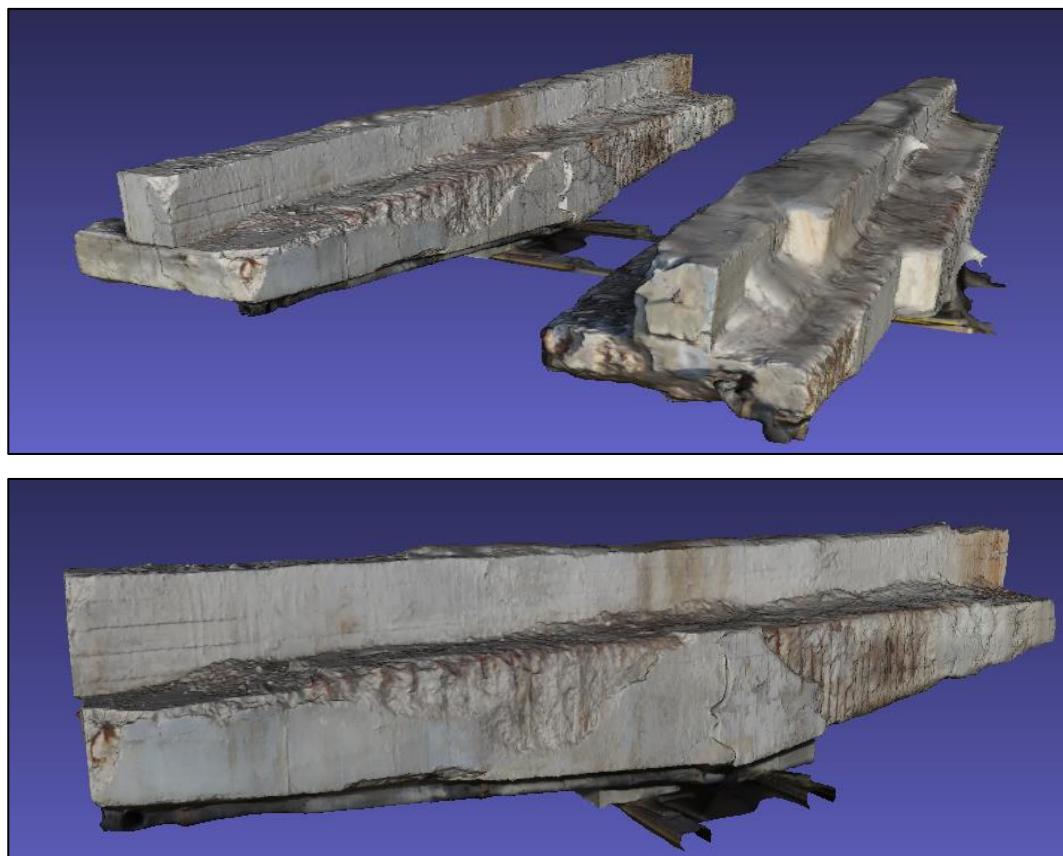
Figure 36. Example of the models after mesh operations.

Next, the compression and simplification process was applied to both divided models. This process is necessary in order to make the triangulated mesh less heavy and complex so it can be more workable and can be managed by other type of software like CAD or BIM software. For this process, MeshLab offers several tools such as "*Simplification: Edge collapse*", "*Simplification: Cluster decimation*", "*Simplification: Quadric edge*", etc. All of these methods allow a reduction in the number of vertexes and faces from an initial number to a target number, by using different methodologies. For example, allow a determined shape of the target triangles, the preservation of particular characteristics of the mesh. Of course, this reduction in the number of faces on the mesh is a key aspect as it implies a reduction of the model quality; trying different reductions in the number of vertices it was found out that an optimal reduction to a number of 10000 faces made a workable mesh in BIM platform without losing fundamental model quality. As it was mentioned before, photogrammetry produces an irregular polygonal mesh, so a reduction of vertex and faces is more noticeable on areas where few, big triangles are located and less noticeable on areas where many, small triangles are located. The *"Simplification: Quadric edge"* tool was selected for this process and the triangulated meshes passed from 415,493 and 523,128 faces for the first and the second pier-cap beams respectively, to 100,000 faces for both models.
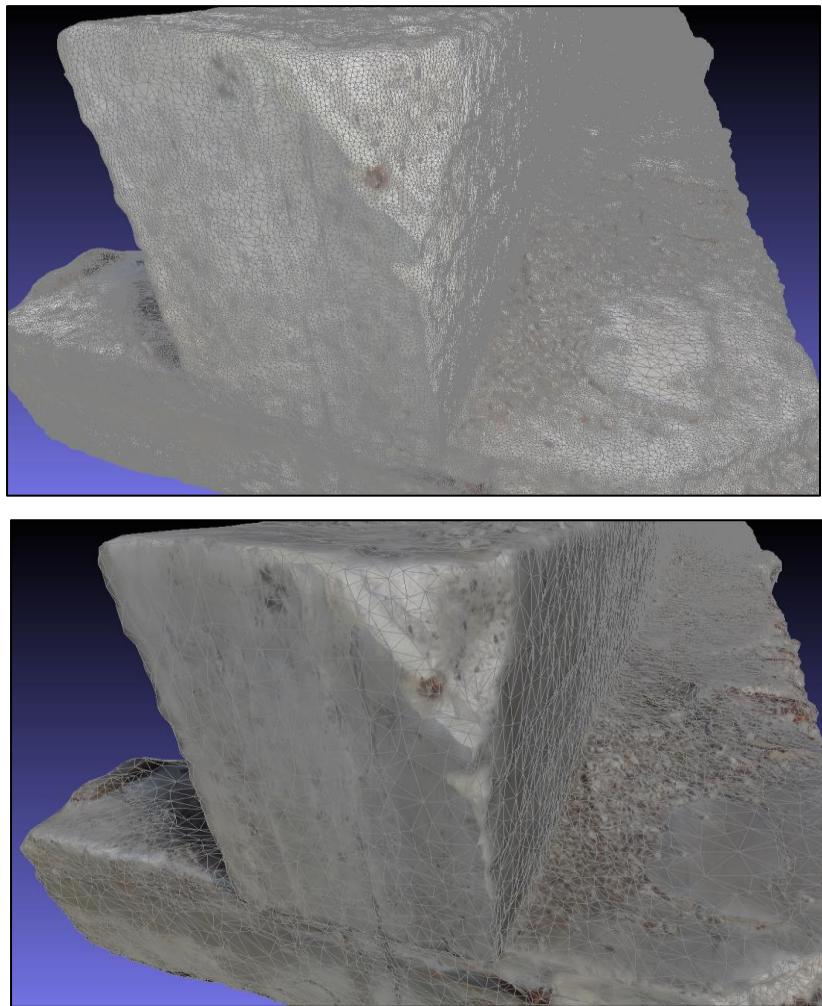
Figure 37. Example of mesh compression.

Finally, with all the operations done on the mesh, the model was ready to export into .DXF format, so it can be uploaded to Revit. On this step, the big interoperability problems between BIM software and photogrammetry software were exposed as this process of exportation allowed the exportation of the geometry, but not the maintenance of the texture, so a no-colored 3D geometry is obtained. This is explained because the .DXF format is a format intended for AutoCAD, and this type of drawing software uses a different type system to set the color into the created elements. In BIM and AutoCAD software, a material needs to be created and applied into the element, while on the photogrammetry software, a color map is created from the images and color parametrization methodology is automatically made to color the model.

This lack of interoperability between software is the main disadvantage of this methodology so in order to color the model again once the geometry is on BIM software a material needs to be created for each planar face of the elements, and an image of that

face is put into the material texture. This implies that before the exportation process of the mesh a "layering" process should be applied to the triangulated mesh, dividing the element into layers according to its planar faces. This is manually done selecting each face of the pier-cap beams with the "*Selection*" tool and a new layer is created for each face with the "*Move selected faces to a new layer"* tool.

Finally, after this last step of layering the triangulated mesh is done, the mesh can be exported into .DXF format to be imported into Revit.

4.1.6 Joining the model with texture information

Once the model 3D object is uploaded into a Revit family template, the process of creating the materials to color the mesh again started. A new material was created for each planar surface layer defined previously on MeshLab and an image was uploaded to give the material appearance. The images uploaded corresponded to frontal photos of each one of the faces of the pier-cap beams that were taken on site. On adobe Photoshop, a picture-editing job was done on each one of these images in order to eliminate the "digital noise" and set the image into the correct scale according to the model. To do this, the "*Magic wand selection"* tool was used to eliminate all of the background and extra content in the image and leave only the texture that was planned to be added to the material. Then, on Revit, the images were set as material texture and its position was carefully determined using the transformation options on the Revit material interface.

Figure 38. Example of image-editing process.

Finally, once this process was repeated for all the layers corresponding to each one of the planar faces of the beam, a phase was assigned to the geometry, so accordingly to what was done with the damages families for the parametric modeling option, the model could be updated and changed over time. With this last step, the model was finished

and the quantity and quality of detail represented allowed a damage analysis that could be done directly on the Revit model.
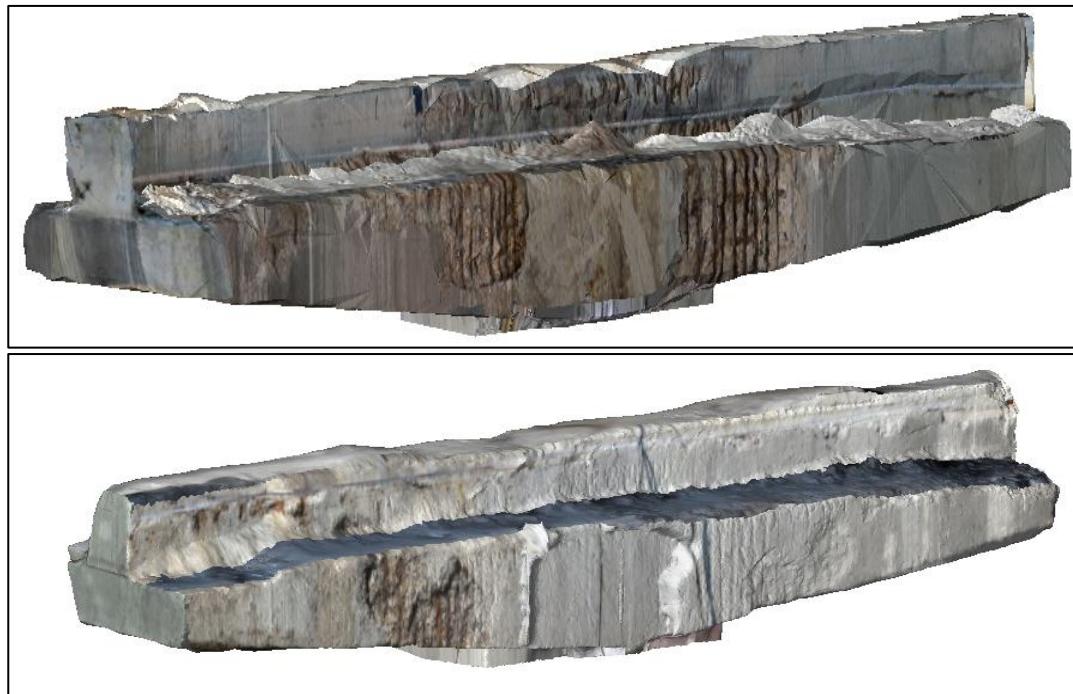
Figure 39. Final representation of the pier-cap beams on BIM environment.

4.2 Stura River Bridge on the RA10 motorway.

4.2.1   In field survey

The processes consisting on the field survey of the Stura River Bridge were guided by the geomatics team of Politecnico di Torino, in charge of Professor Marco Piras.

The first part of the in site survey consisted on the topographic survey in order to create a topographic framework and determine the coordinate system with respect to a unique reference point. The coordinates of the initial unique point were obtained thanks to the GNSSS system (Global Navigation Satellite system). This operation requires the positioning in the selected point of a GNSS receiver, which communicates with at least four satellites in order to obtain the X, Y, Z coordinates of the point. Two points are required as an input in order to obtain a closed network. The instrument used for this operation was a Leica GPS System 1200. In order for the antenna to receive the signal from the satellites with accuracy, it should be located far away from obstructions such as trees or closed spaces. Due to this restriction, the antenna is situated on an open space to the right and to the left of the bridge abutment and then with a total station (Leica ms50)

positioned on a tripod under the first span of the bridge and a reflector, the coordinate network can be created.

Figure 40. GNSS/GPS survey

While this operation occurred, different members of the team positioned rectangular markers (Visual inspection accessories to represent easily locatable points on the model) on different points of the surface of the intrados of the bridge. The usage of these markers allows the correct orientation and determination of scale factor on the model obtained from the laser scanner/photogrammetry, as they are easily recognizable on the point cloud and its coordinates can be obtained with triangulation calculation taking into account the measurement taken on site. The number and location of the points was chosen in order to cover completely the first span of the Stura River Bridge. These points were carefully enumerated in an inspection sheet in order to then locate it and report it on the model. Then with the usage of the total station, measurements of the vertical and horizontal angles, as well as the slope distance from the instrument to the required point are obtained. For each point, this information is obtained in order to later on perform triangulation calculations and find the point coordinates.

Figure 41. Markers positioned in bridge surface and total station used.

Once the measurements from the total station were finished, the process of laser scanning started. Fourteen laser scans were made with the instrument FARO CAM 2'' positioned on a tripod. The number of scans made was determined considering covering completely the surface of the bridge. Taking into account this situation, four laser scans were made after the first piles of the bridge, one in between these first piles and nine between the abutment and the first piles.
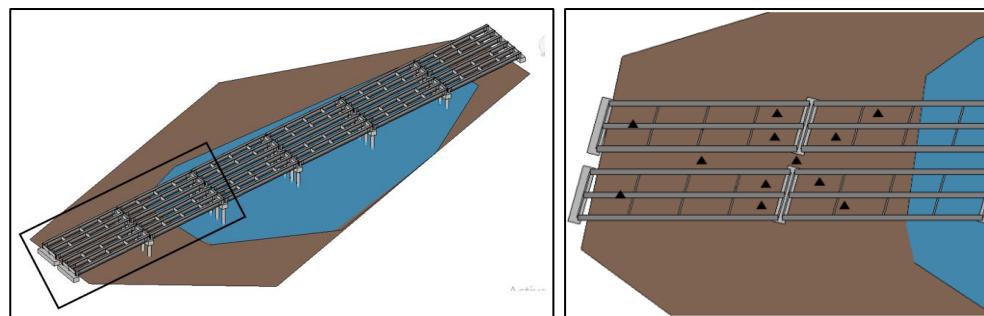
Figure 42. Illustrative positioning of the laser scans performed.

Figure 43. Laser scan performed on site.

The success of the laser scanner is conditioned by the fact that at least two same markers (preferably three) are present in different scans. This allow the processing software to correctly recognize the geometry of the positioned object when creating the 3D point cloud. The resolution and quality characteristics of the instrument were configured on site and the data acquisition process started.

The final step of the on field survey consisted on the photogrammetric survey. This part was divided into aerial photogrammetric survey by the usage of the UAV and terrestrial photogrammetry. The terrestrial photogrammetry survey was performed thanks to a Nikon d800e camera with lens bm-hv40. The main characteristics of this camera are a 36.3 Megapixel full (35.9 mm × 24 mm), and sensor with ISO 100–6400 (ISO 50–25600 boost). On the other hand, the aerial photogrammetry performed represented a novel, experimental procedure for the geomatics team as for the first time the survey was realized with the camera positioned on the drone looking upwards to survey the bridge intrados instead of downwards as it normally occurs. For the survey was used a drone Phantom dji 4 previously modified by the geomatics team. This drone was equipped with a raspberry pi operative system in order to control a camera module of 8mp positioned upwards in a 45 degrees angle. The drone used had a flight autonomy of around 15 minutes and the camera installed allowed the capturing of 500 photographs per flight. The drone flight was manually executed as no flight plan was previously created, assuring a complete survey of the bridge intrados and overlapping of images of in longitudinal direction and in transversal direction. Two flights were performed during this survey, which produced more than 700 photographs in *.jpeg* format.

Figure 44. Modified drone during the survey activity.

4.2.2 Elaboration of the Point clouds

Once all the information from the on-site survey was recovered, the first step to be followed was to organize and subdivide the data collected taking into account to what type of information they indicated.

Considering that the survey performed recovered information from three different sources (GPS/GNSS, LiDAR and Photography –UAV, Terrestrial-), three separated procedures were done to analyze each type of data and then were joined together. These operations were supervised and realized thanks to the collaboration with the geomatics team so they are not going to be described as on detail as on the previous study case, but mainly theoretical concepts of the work completed are mentioned.

As a first procedure, the Starnet software was used in order to register the coordinates of the initial points acquired thanks to the Leica antenna. As the original survey was made through the GNSS system a conversion to a local geoid coordinate system was made. Then, after the triangulation process of the data obtained by the total station about the markers, the coordinates of these markers were also imported into the project. A process of compensation of the originally obtained coordinates was made taking into account the possible biases caused because of error propagation. The final output from this procedure is a text file in a *.csv* format in which the name and coordinates (X, Y, Z) of all the markers is obtained in the local reference system.

The next step consisted on the processing of the 14 laser scans made on the software Faro Scene. The first action made on this software consisted on the importation of the scans into the workspace of the software. Then, a process of automatic pre-processing of the scans was made in order to guarantee the correct positioning of the scans. This process was made takin into account the markers that were positioned on the surface of the bridge during the survey. This success of this pre-processing procedure is conditioned by the fact that at least two same markers are present in different scans. In this case, this condition was fulfilled in all scans, so the scans could be correctly positioned in order to continue on the recognition work for the next processing steps. Afterwards, the scans were taken into a "plane view" in order to recognize the markers placed on field. The operation of recognition of the markers can be made automatically by the software, however, a manual work was preferred on this case to avoid an over estimation of markers in the model. Once a marker is individuated, the command *"Create object"* is used so that the number of

points that represent the marker is selected and grouped together as a single object and a name and description can be assigned. In addition to the markers, the natural points (Points that did not have a marker positioned during the field survey, but due to their characteristics are particularly easy to recognize in multiple scans) that were measured during the survey process were also identified and grouped so a number can be assigned to each one of them. After all markers and natural points were individuated, the text file that contained the coordinates of the points is loaded into the model. Then, using the command "*place scans on target*" a coordinate is assigned to each marker.

After all targets from every scan are georeferenced, the process of processing the scans -merging all scans together in order to obtain a unique point cloud- is effectuated. To do this the command "*ScanManager*" is used. This option allows setting parameters in order to delete repeated points as well as an option to homogenize the final point density. After the scans are joined together, the tab "*Properties*" is used to recognize the error in this process. To calculate this error, the software compares the scans that contain two same markers or natural points and displays the error of location in mm for these points. From this tab, it can be seen that the scans result almost perfectly joined with an error in a milimetric scale. The final step on this software is the coloring and exportation of the point cloud. In order to color the point cloud, the command "*Color*" and *"Set Image"* are used. The color then comes automatically to the point cloud as during the survey on field the RGB properties of each point were also registered. From the point cloud obtained it can be seen that the zones of the piles is very densely detailed, capturing almost perfectly the wanted geometry, however, for the intrados of the deck, some voids are present, as the laser beams were not able to reach certain angles.
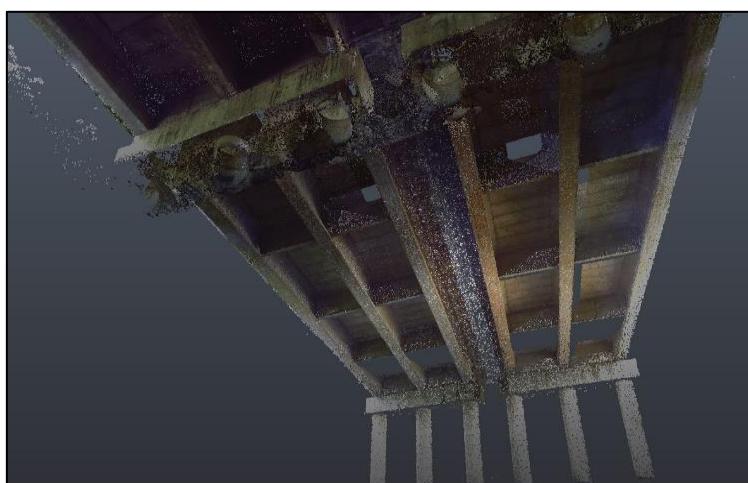

Figure 45. Cleaned point cloud obtained from laser scanners.

For the creation of the model from the photographs, it was decided to use only the photos taken by the UAV flight, taking into account that the results from the laser scanner already captured in a correct manner the geometry of the piles. To do this, and following recommendations by the geomatics team, the software Autodesk Recap was not used, but it was decided to use the software Agisoft Metashape. To this software 650 pictures from the UAV were imported, excluding from the importation process some photos that resulted blurred, were repeated or contained mainly digital noise. As all the pictures imported to the model were taken from the same camera no need of camera calibration was needed, however, the quality of the images was measured in order to detect the worst images and not consider them for the creation of the model. Once the correct pictures were selected, the next step corresponded to align them in order to build the sparse point cloud. To do this, the software automatically recognize the key points and tie points present in the images and use them to create the sparse point cloud. The software allows the user to set the accuracy of the alignment to be performed, which in this case was set to high. This process was expected to be really critic step on the workflow as the images used were extremely similar one to the other. Moreover, the light conditions were considerably different from one side of the bridge deck to the other creating difficult conditions for the image alignment. However, even with these unfavorable situations, the photos could be correctly aligned and the process of creation of the point cloud continued.

Figure 46. Example of images obtained by the UAV.

After the sparse point cloud was created, the process of geo-referenciating the model started. Similarly to what was done to the point cloud created by the laser scanners, the text file with the coordinates was also loaded into the workspace of this software. Then, a process of manually individuating the markers in each photogram is done. To do this, the command "*Place marker*" is used and a coordinate is assigned to each marker. This process does not need to be applied to each photogram, as after some manual work the

software is able to automatically complete the task for all of the other images. Clearly, this process is not only done for the markers but also for the natural points that were measured on field. Finally, the software allows the visualization of the error in the model comparing location of the markers in the photograms. On this case, the error is situated in the cm scale. This error may seem big for certain projects, but considering the fact that this survey was made following a novelty approach in terms of the camera (whose quality was not the greatest) mounted manually on an inversed position, without any stabilizing mechanism, is considered acceptable. After the process of geo-referenciating the sparse point cloud is done, the process of building the dense point cloud starts. In this step is possible to set quality for the cloud generation. This parameter refers to how many common points or pixels in the images are looked for and chosen in order to create the dense point cloud. Of course, the higher it is the better the model is but the heavier the model is and the more computational time it requires for processing. In this case, a high quality is chosen. The process is set to run and after the necessary processing time, the dense point cloud is generated.
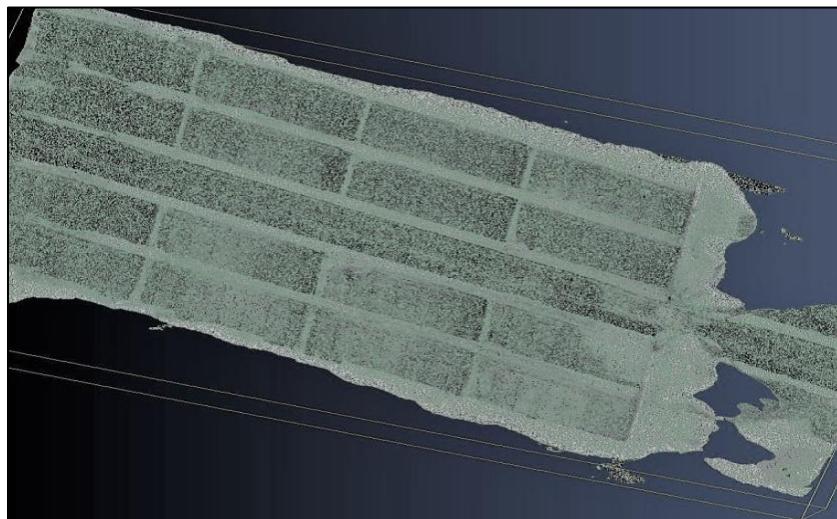
Figure 47. Point cloud obtained from the UAV flight

As it can be seen from the point cloud obtained, this only includes the intrados of the deck of the bridge, as the drone did not take photos of the piles. This was a great result, considering that the point cloud obtained from the laser scanner contained almost perfectly the piles, but not so accurately the intrados.

Considering this situation, it was decided to continue using the complete point cloud generated by the UAV survey and create section box of the point cloud generated by the

laser scanner in order to only take into account the first (situated on land) and second (situated on water) piles and pier caps of the bridge. To do this selection, the tool cut with polygon was used inside the Faro Scene software and the wanted piles/beams from the bridge were selected.
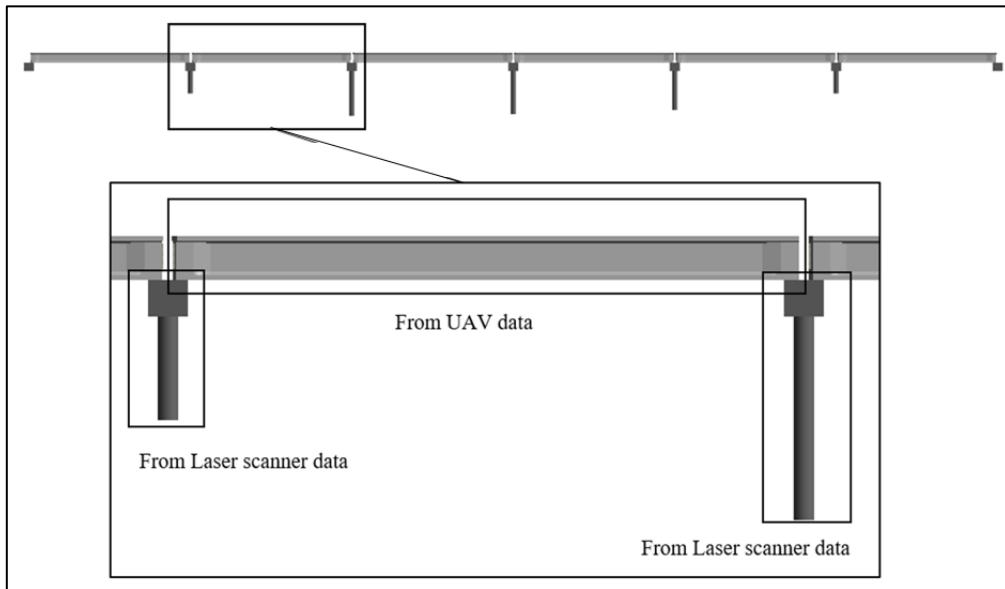
Figure 48. Subdivision of point clouds for the creation of the mesh.

From these models, it is important to remark that the number of points close to the first piles/pier cap is much greater than the one for the second piles/pier caps. This difference is explained due to the closeness of the first piles to the scanner and because these piles were visible from the 14 scans while the other ones only from the first 4 ones.

From the point clouds obtained the following information was recovered:

Table 9. Details of original models.

Faro Scene – Laser scanner survey – Original data		Agisoft metashape – UAV survey – Original data	
Number of points	243.026.283	Number of points	3.467.112
Model size	6,02GB	Model size	46,4 MB

Faro Scene – Laser scanner survey –Section box- Piles 1		Faro Scene – Laser scanner survey – Section box- Piles 2	
Number of points	18.326.217	Number of points	1.356.284
Model size	613 MB	Model size	20,4 MB

4.2.3   Point cloud operations and triangulated mesh operations

As it can be seen from the table 9, an enormous amount of data was recovered from the survey performed and consequentently massive point clouds were produced when processing the data. This quantity of data implied that the computational resources needed in order to process and manipulate the information would be equally demanding.

Initially, the processing of this information was taken place in an Asus computer with Intel core i5, 512GB SSD, 8GB ram and an integrated Intel UHD graphic card; however, the size of the data made that the operations to be performed did not respond correctly on this of computer. Consequently, thanks to a collaboration with the BIM team of Politecnico di Torino, a new computer with more robust characteristics was facilitated in order to continue the work operations. The new computer was an HP Zbook with an Intel core i9, 512GB SSD, 16GB ram and an NVIDIA Quadro RTX 3000 graphic card.

Nevertheless, the large amount of data caused that even when using this new compute with better performance simple operations like orbit around the cloud or selecting points implied excessive running time and even lag or total crash in the software. Considering this situation, and that the final output to be transported it into a BIM software should be of a much more reduced size, a decimation process was the first operation performed to the point clouds.

Decimation is common process when using high-resolution point clouds data in order to reduce the memory requirements and computational time demand. This process means setting a grid size and using the space of this grid and the point values that are contained within it to define the number of points to be discarded and the number to remain.

This process needs to be carefully performed so that the cloud remains in a more workable size without losing its quality. This balance between quality/computational size was performed in a trial-error iteration process decimating the clouds in small quantities until an optimal result was obtained. The final output of the decimation operation is shown in the following table:

Table 10. Point clouds after decimation process.

	Agisoft metashape - Intrados	Faro Scene - Piles 1	Faro Scene - Piles 2
Number of points	1.220.765	5.652.011	1.356.284
Model size	20,2 MB	112,7 MB	20,4 MB

As it can be seen on table 10, the more drastic change due to the decimation operations was reflected on the point cloud from the first piles/pier caps. This is explained because this is point cloud was de most defined one, with many points practically overlapping one to the other. Understanding that the quality of the point clouds does not need this level of detail for this type of analysis and that all of the point clouds produced should have a similar order of magnitude in terms of cloud definition, the decimation operations for this specific point cloud were more severe than for the other ones.

Then, after the decimated point clouds from both software were ready, the next steps included the operations in order to prepare the point cloud for the creation of the mesh.

The first operations made for this task consisted on the elimination of digital noise. The *"Section box"* or *"segmentation"* tool was selected on both software in order to create "sections" of the point cloud to which is easier to work in. In these sections, the "*select*" tools was used for the elimination of the digital noise through a manual process. This process is crucial for the correct creation of the mesh, as the triangulated mesh considers all present points in the point cloud and the digital noise may create bumps or unwanted deformations in the geometry. After most of the digital noise was eliminated, the mesh could be created. Both software presented the option to create the mesh internally; however, the mesh obtained on Faro Scene was not of a good quality. This can be easily understood, as this software does not aim as a principal scope for mesh creation/editing but for point cloud generation from scans. Because of this situation, the two point clouds from this software were exported in .PTS format and imported into MeshLab for the creation of the mesh.

Both point clouds were imported into different MeshLab projects, but the same operations are made to each one of them. Once the point clouds are in MeshLab, the first step to create the mesh is to compute the normal of the points with respect to the vertical axis. For this task the "*Normal filter – Compute normals"* is used. This filter captures groups of points and creates planes from these groups of points to calculate the normal with respect to the Z-axis. Once the normals are computed, the mesh can be created. To do this, the "*Mesh surface reconstruction filters*" are used. This group of filters provide a set of different algorithms to create meshes from a 3D point cloud. Following recommendations from the literature, the filter chosen for the creation of the mesh is the Poisson surface reconstruction (Furukawa et al., 2009). As this filter consider all the

points at once to the product is highly sensitive to data noise. Moreover, this filter tries to recognize geometries, so problems are presented in sections were not a clear geometry is presented. For example on the second piles (The ones on water), only points from the frontal part were captured by the laser scanner, as only were surveyed from one side of the bridge. This means that instead of a circular pile, as it should be in reality the points represented a void semi-circular shape, taking into account the surface surveyed. These problems implied a high number of manual operations to be applied to the obtained mesh, decimating and cancelling mistaken geometries generated by the algorithm.
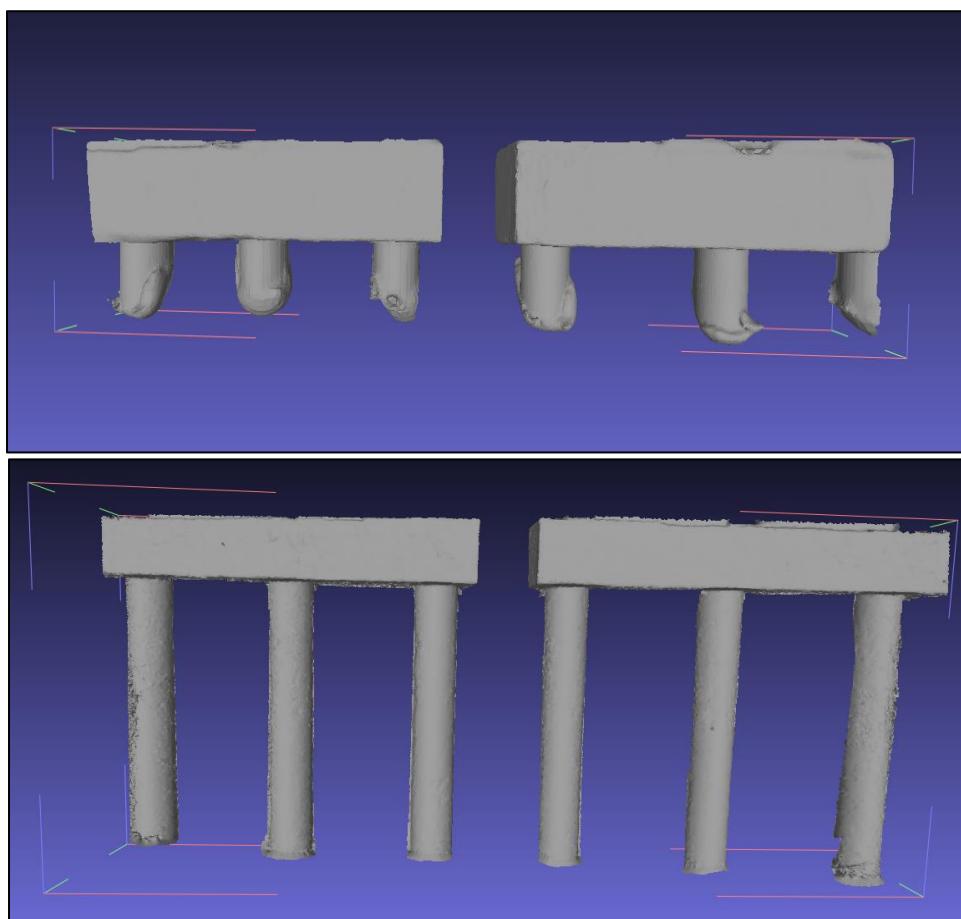
Figure 49. Meshes of pile and pier caps obtained from laser scanner data.

On the other hand, the triangulated mesh created by the software Agisoft presented an optimum quality, with a low quantity of voids and no major problems because of the geo-referentiation error. However, the mesh also presented some irregular bumps that modified the geometry because of some digital noise that could not be previously eliminated. As well as it occurred for the creation of the dense point cloud, for the creation of the mesh this software also allows the choosing of the quality in the model, that in this case was set to High. As the mesh created was of a good quality the next step on the

workflow was the creation of the mesh texture. This means to use the radiometric information of the images in order to create "paint" to give the correct color detail to the mesh. To do this the option *"Build texture"* is selected and the diffuse map option is chosen. Once the mesh is correctly texturized, it is ready to be exported in .OBJ format and imported into MeshLab to be joined with the information coming from the laser scanner.
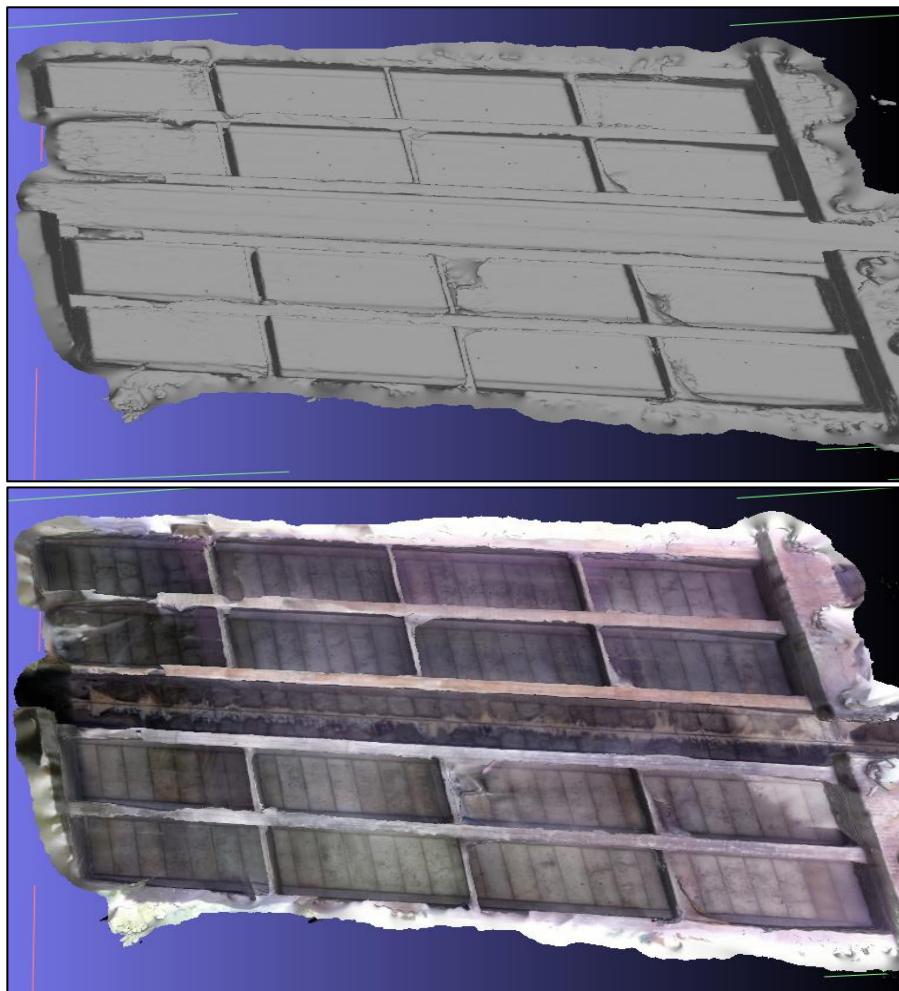
Figure 50. Mesh intrados obtained from UAV data.

Once all the meshes were imported into a single MeshLab project, there was no need of relocation or resizing the meshes, as they were all georeferentiated. On the contrary, processes of cutting extra geometries on the elements to make a perfect fit of the meshes coming from different survey methodologies was needed. These operations were manually made with the "*selection*" and "*delete faces*" tools. After the meshes fitted perfectly one to the other the *"Alignment"* and *"Flatten"* tools were used in order to merge the three meshes into a single one. Then, to this unique mesh, the same operations that were applied on the mesh of the previous study case were done in order to prepare

the mesh for the final importation to BIM software. This is, fixing operations, operations of compression/decimation and operations separation of elements into layers.

For the fixing operations, the "*Fill holes*" tool was used. With this tool, all voids greater than 0.01m were selected and filled in order to have a completely closed mesh. As explained before, this tool selects voids and fills them with a new face without texture, so a few new faces without color appeared into the model to create a complete closed object. Then, in order to guarantee the workability of the triangulated mesh inside MeshLab software (and later on inside BIM software), the compression and simplification operations were made. As on the previous study case, the *"Simplification: Quadric edge"* tool was also used for this process. On this study case, also an irregular triangulated mesh is produced, so the principle of differential loosing of quality depending on the number of vertices explained on the study case 1 also applies on this mesh. With this reduction, the mesh passed from 953,293 faces to 672,547 faces.
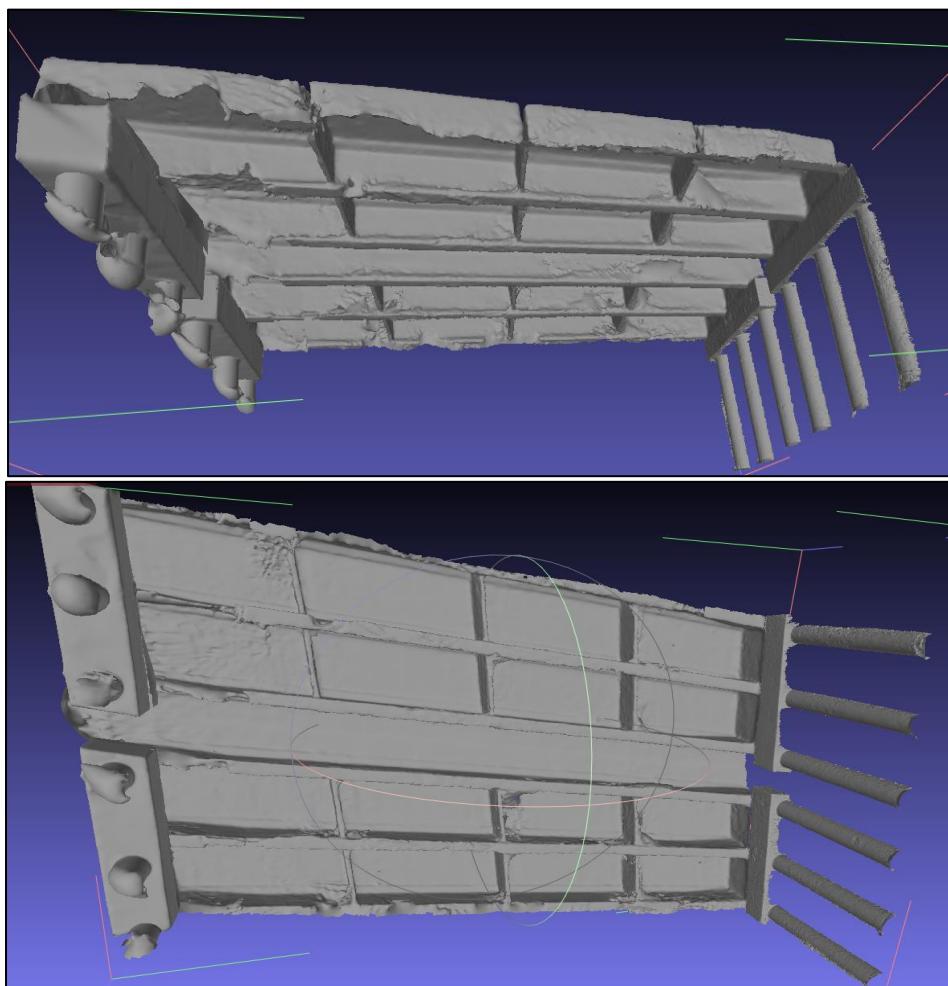

Figure 51. Final mesh obtained for the Stura Bridge.

The last operations to be made correspond to the "layering" process in order to surpass the interoperability problems that cause the loosing of texture when passing to Revit. Once again, this is manually made selecting each planar face of the element with the "*Selection*" tool and a new layer is created for each face with the "*Move selected faces to a new layer*" tool. This process make each planar surface of each model independently editable, so that a material can be assigned inside BIM software.

Finally, after all this triangulated mesh operations are done, the mesh can be exported into .DXF format to be imported into Revit.

4.2.4   Joining the model with texture information

Due to the interoperability problems between triangulated meshes and BIM software, a new material needs to be created for each planar surface layer defined previously in order to color the object once again. To these new materials, a frontal photo of each one of the faces is uploaded in order to give the material the right appearance.

These pictures were obtained using the command "*Ortho-photo*" from the software MetaShape and Faro Scene. As the survey did not contemplate all the bridge geometry completely is clear that not all surfaces of the mesh created will have a corresponding texture. For example, the part conforming the intrados of the bridge will only have a texture corresponding to the inner section, but the sides or the upper part of deck or the lateral sides will remain un-colorized on the mesh.

Then as it was done on the first study case, the ortho-photos obtained needed a picture-editing job so that the "digital noise" is eliminated and the correct scale factor is set. As previously explained, the "*Magic wand selection*" tool was used on Adobe Photoshop to eliminate all of the background leave only the planar faces of the elements. Finally, on Revit, the position of the images inside the elements layer was carefully determined using the transformation options on the Revit material interface. This process was repeated for each one of the planar surfaces of each one of the elements on the model.

Figure 52. Example of orthophoto used for the texture of the intrados.

4.2.5   Creation of the Revit model

Taking advantage of a parametric model of the bridge already created for a previous thesis, the mesh in format .DXF was imported into this model in order to compare the results with the model created with the traditional approach. To do this, the elements of the parametric model corresponding to the elements of the mesh, were deleted in the model, and the imported mesh was positioned in its place. As it was found, there was a perfect match between the mesh imported and the created model, which means that the geometry of the parametric model previously created corresponds correctly to the surveyed bridge. The only difference found between the geometry of the parametric model and the mesh corresponds to the length of the piles, difference that is understandable because the parametric model was created considering the length from the design while the mesh only takes into account the visible part of the piles from the survey.

Then, after the mesh was correctly positioned inside the model, the materials corresponding to the layers were created and the images previously prepared were assigned as texture and correctly aligned to each one of the planar surface of the mesh. Finally, a visibility graphics filter of transparency was set for the upper deck of the bridge in order to facilitate the viewing settings for the Revit user. At the end, it is possible to evidence the difference between the model created parametrically and the one from the mesh, and how the quality of the one created from the remote sensing technologies allowed a damage characterization inside the model.
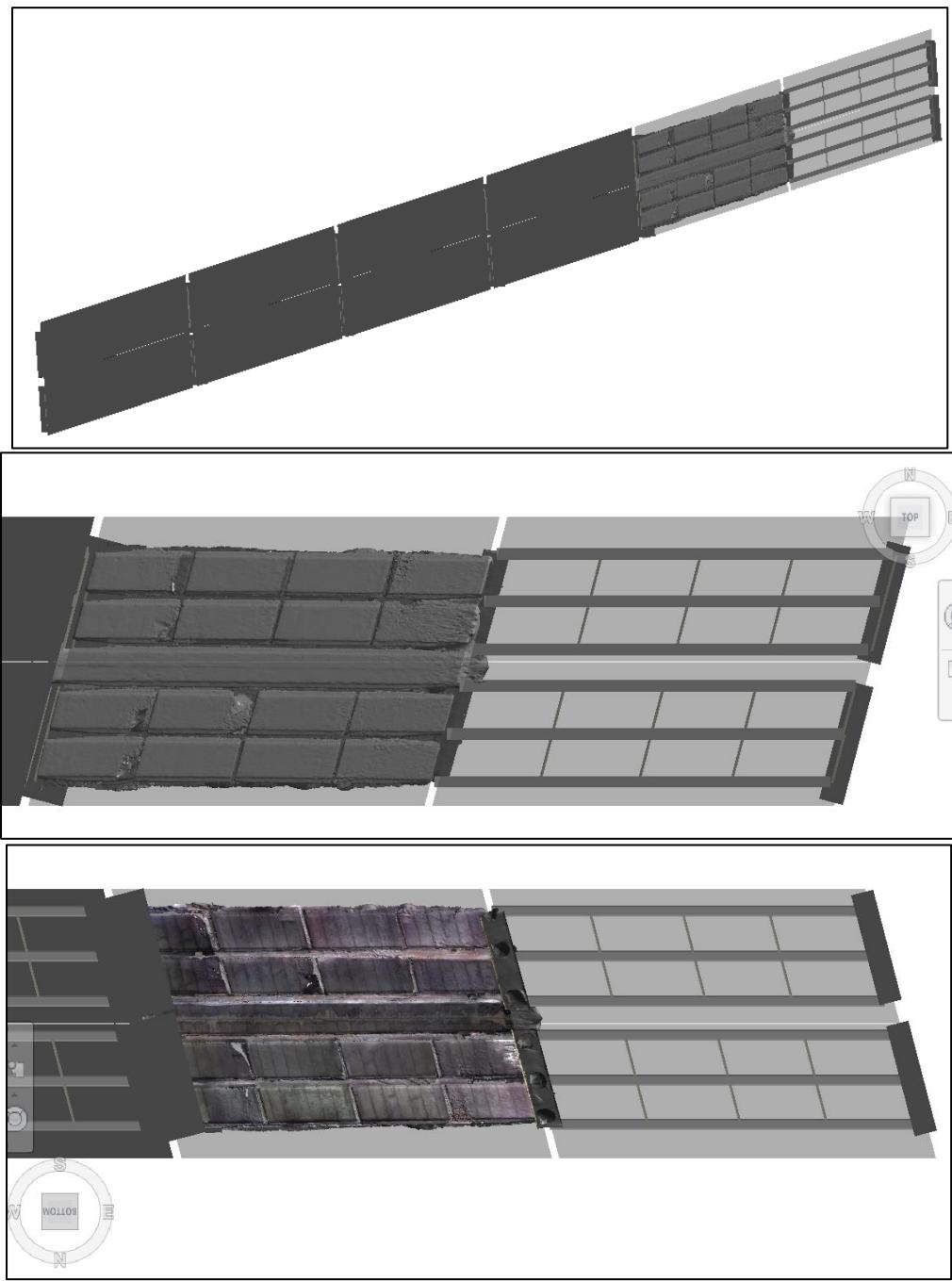
Figure 53. Final model obtained - Bottom and top view

Figure 54. Final model obtained - View of the piles.

4.2.6   Creation of the damage inspection interface

After the Revit model was complete, the damage characterization and analysis process could be done. The idea on this section is that the damage characterization can be made directly inside the Revit model following the new Guidelines for bridge monitoring of the Italian Government. Specifically, the level 0 and level 1 of this guideline focus on the census, geo-localization, general characterization and direct visual inspection of the bridge so this are the levels that are intended to be realized on the BIM platform.

In order to do this, the sheet card for level 0 and the sheet card for level 1 were recreated in a user interface in BIM using the visual programming software Dynamo. The original data sheets of both levels can be retrieved on the annexes. With the purpose of the user interface to work correctly, many additional no-geometry families needed to be created before, so all the parameters and information requested by the sheet cards can be followed from the inspector. All these new families were created on generic model

template and without any geometry, but only parameters, so that the information can be inserted into the model.

Moreover, a several set of scripts were created with Dynamo so that once the technician has some specific information required in the guidelines can easily insert it into the project. When these scripts are run a user interface is shown, and a series of question about the information from the guidelines is displayed. Then, according to the technician answer, the information is added to fill the family parameters and a family instance is created in the project. Additionally, for the level 1 (Damage visual inspections) the technician is given the possibility to insert a label to the model, so that the damage position is well known from a 3D general view. This label is a sphere shaped notation system whose color and diameter change according to the damage weight (G), extension (K1) and intensity (K2) parameters.

Finally, when all the damage characterization and information required from level 0 and level 1 is inserted into the project additional scripts were created in order to export the information into excel sheets.

The following section indicate the different scripts that were created and the families that they use:

- **<u>Level 0 – Part 1 – General information and positioning</u>**

Families:

- Censimiento – Dati Generali
- Censimiento – Localizzazione

Information to be recovered

- General information about the bridge characteristics
- General information about the bridge position and site

Parameters

- Bridge name
- Bridge code
- Belonging road
- Initial/Final Progressive

- Region/Province
- City/Locality
- Seismic parameter (ag)

- Initial geographic coordinates
- Center geographic coordinates

- Final geographic coordinates
- Bridge state
- Bridge typology
- Belonging road classification

- Site morphology
- Bridge length
- Bridge width
- Bridge span number
- Bridge span length

- Bridge layout
- Hydraulic/ geotechnics characteristics

Code description

This user interface was created thanks to the Dynamo package Data Shapes. In this script, four different windows are opened to the technician in order to fill the needed data.

- Window 1: Information about general bridge characteristics is requested. According to the user answer parameters from the family *"Censimiento – Dati Generali"* are filled.

Figure 55. User interface and code for damage inspection - Level 0 -General information - Window 1

- Window 2: Information about bridge localization is requested. According to the user answer parameters from the family *"Censimiento – Localizzazione"* are filled.

Figure 56. User interface and code for damage inspection - Level 0 -General information - Window 2

- Window 3: Information about bridge geometric characteristics is requested. According to the user answer parameters from the family *"Censimiento – Dati Generali"* are filled.
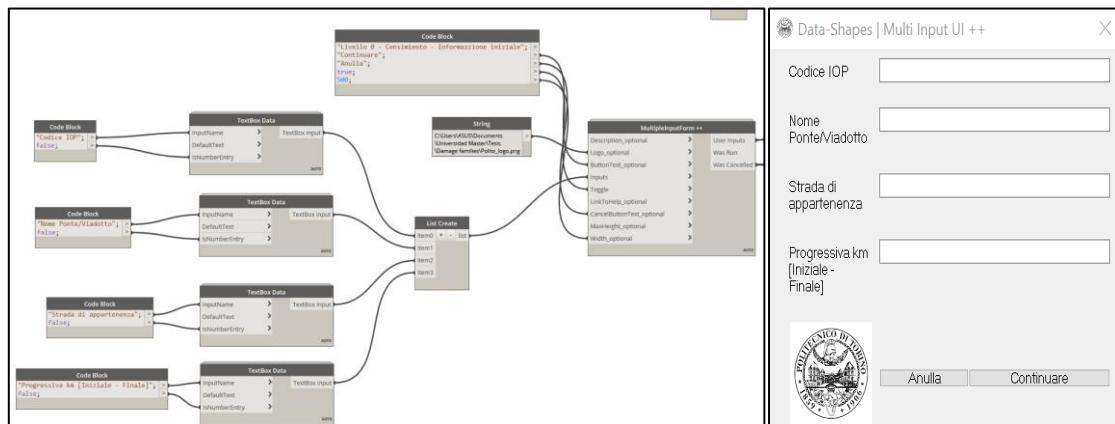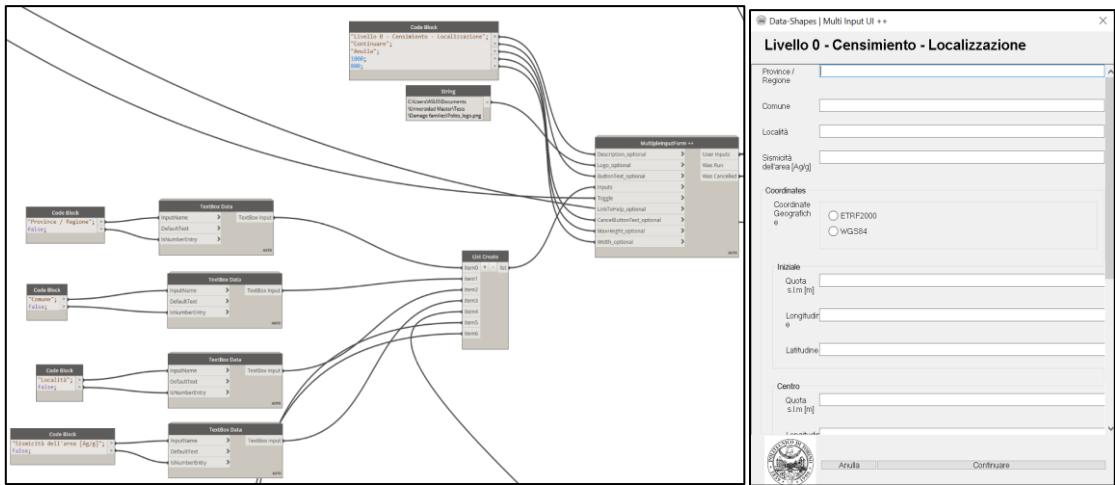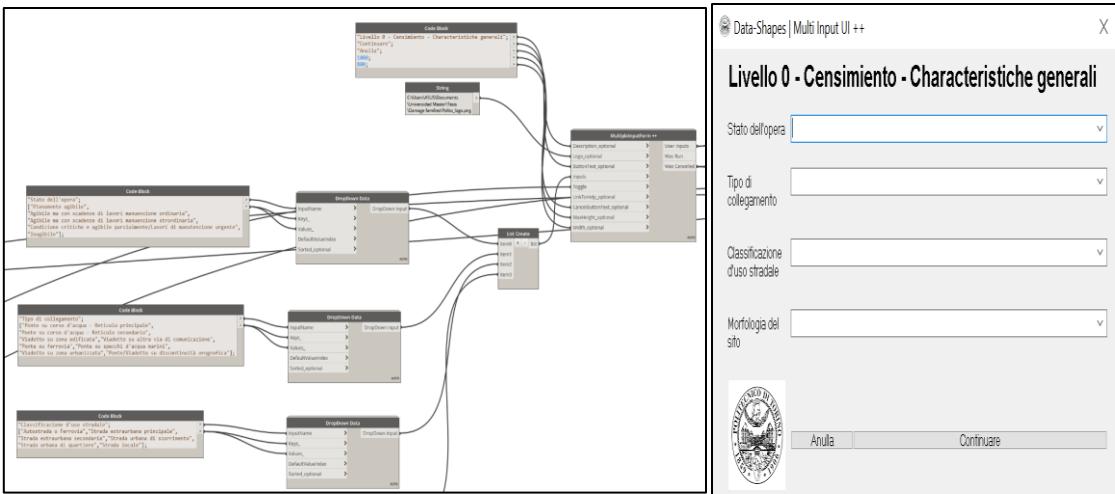

Figure 57. User interface and code for damage inspection - Level 0 -General information - Window 3

- Window 4: Information about bridge localization is requested. According to the user answer parameters from the family *"Censimiento – Dati Generali"* are filled.
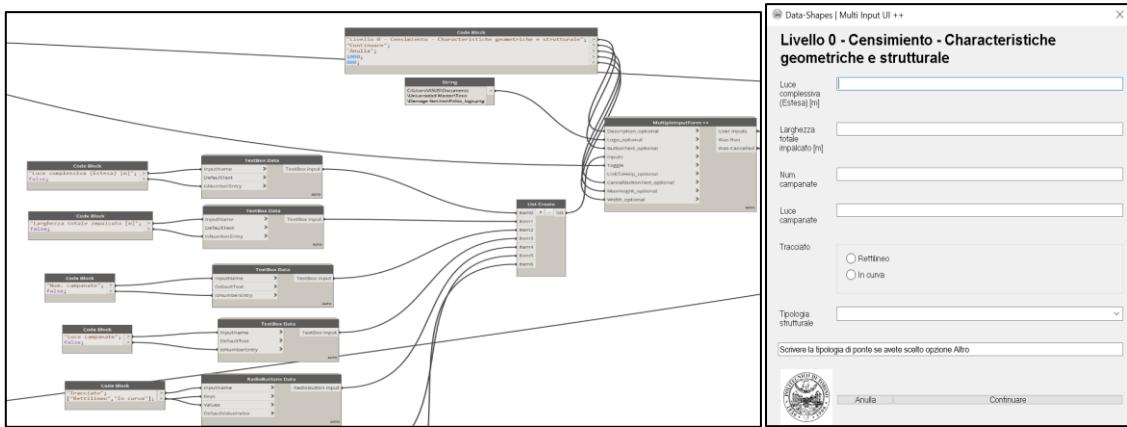
Figure 58. User interface and code for damage inspection –Level 0 -General information - Window 4

- **Level 0 – Part 2 – Data and available documents**

Families:

- Censimiento – Dati di progetto
- Censimiento – Documenti

Information to be recovered

- Information about bridge owner, design and construction.
- Information about the bridge available documents. For all documents available the annex number and reference is required

Parameters

- Owner
- Operator
- Supervisor
- Designer
- Design Approver
- Design code used
- Design year
- Construction year
- Initial documents

- Preliminary project documents
- Definitive project documents
- Executive project documents
- Project management documents

- Construction site documents
- Supervisor documents
- Inspection alert documents
- Maintenance documents

Code description

This user interface was created thanks to the Dynamo package Data Shapes. In this script, three different windows are opened to the technician in order to fill the needed data.

- Window 1: Information about bridge owner, constructor and construction dates are requested. According to the user answer parameters from the family *"Censimiento – Dati di progetto"* are filled.
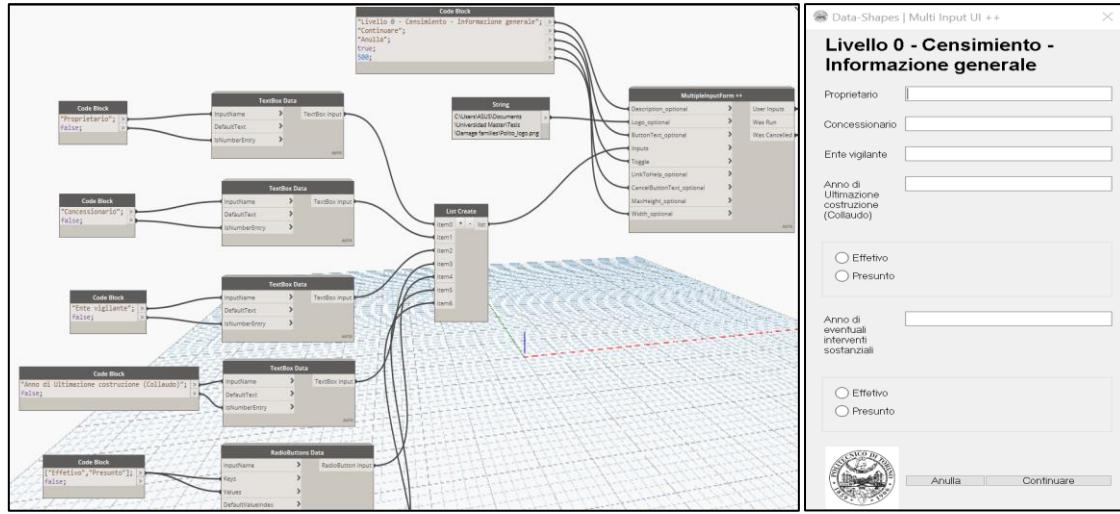
Figure 59. User interface and code for damage inspection - Level 0 -Data and documents available - Window 1

- Window 2: Information about bridge designer, code, supervisor and design dates are requested. According to the user answer parameters from the family *"Censimiento – Dati di progetto"* are filled.

Figure 60. User interface and code for damage inspection - Level 0 -Data and documents available - Window 2

- Window 3: Information about bridge available documents is requested. A table including all possible documents is displayed and the user should indicate which documents are available its reference and annex. According to the user answer parameters from the family *"Censimiento – Documenti"* are filled.
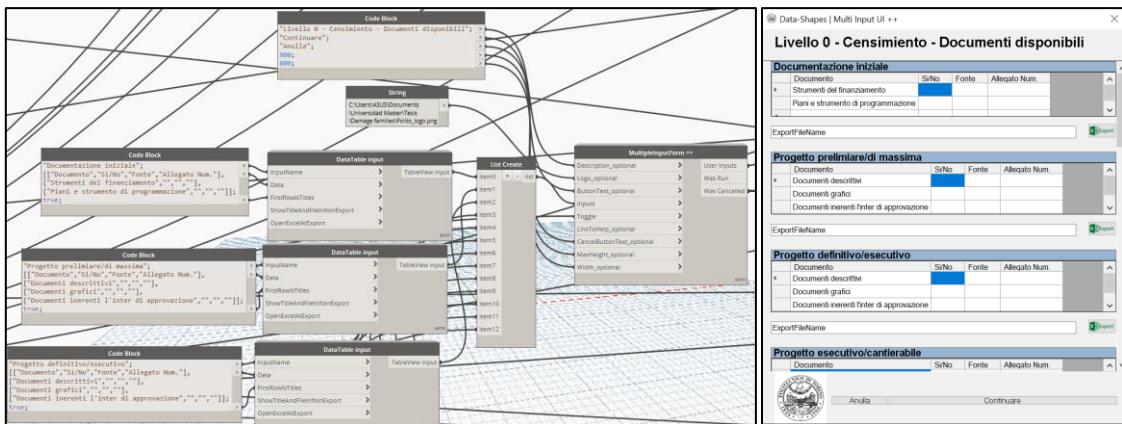
Figure 61. User interface and code for damage inspection - Level 0 -Data and documents available - Window 3

- **Level 0 – Part 3 – Bridge elements**

Families:

- Censimiento – Pile
- Censimiento – Giunti
- Censimiento – Spalle

Information to be recovered

- Information about bridge piers
- Information about bridge joints
- Information about bridge deck
- Information about bridge abutment
- Information about bridge abutments

Parameters

- Initial abutment typology	- Pier cross section	- Barrier system type
- Final abutment typology	- Pier typology	- Bearings typology
- Foundation initial abutment	- Pier foundation typology	- Anti-seismic system
- Foundation final abutment	- Pier height	- Joints typology
- Pier material	- Pier geometry	- Joints quantity
	- Pier foundation number	- Joints length
		- Joints width

Code description

This user interface was created thanks to the Dynamo package Data Shapes. In this script, three different windows are opened to the technician in order to fill the needed data.

- Window 1: Information about bridge abutment is requested. According to the user answer parameters from the family *"Censimiento – Spalle"* are filled.
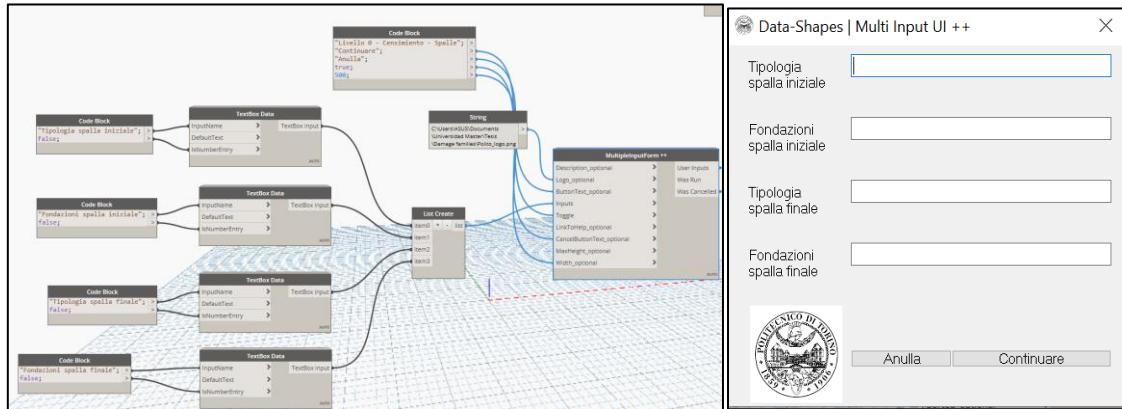
Figure 62. User interface and code for damage inspection - Level 0 -Bridge elements - Window 1

- Window 2: Information about general bridge piers is required According to the user answer parameters from the family *"Censimiento – Pile"* are filled.

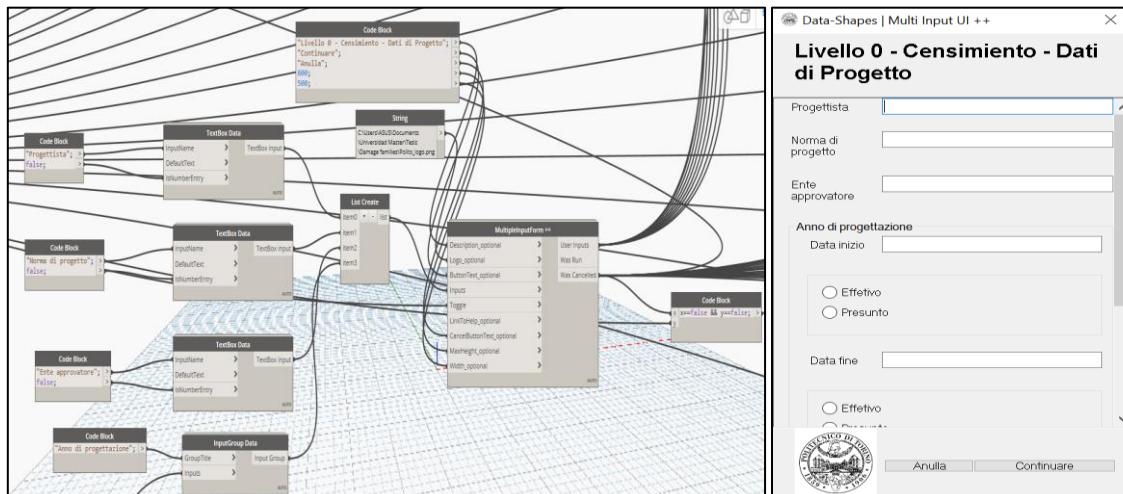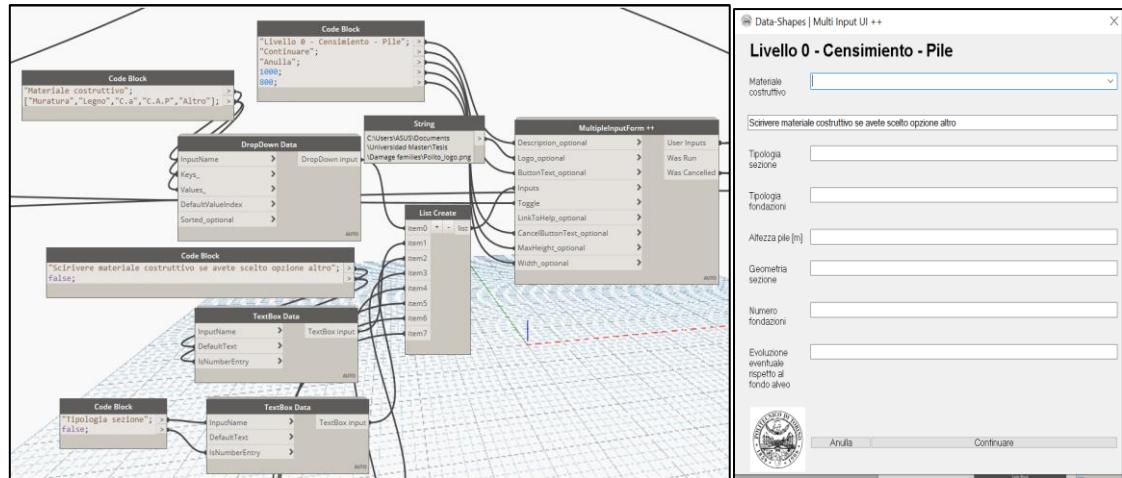**Figure 63.** User interface and code for damage inspection - Level 0 -Bridge elements - Window 2

- Window 3: Information about bridge joints, bearings, deck and barrier According to the user answer parameters from the family *"Censimiento –Giunti"* are filled.
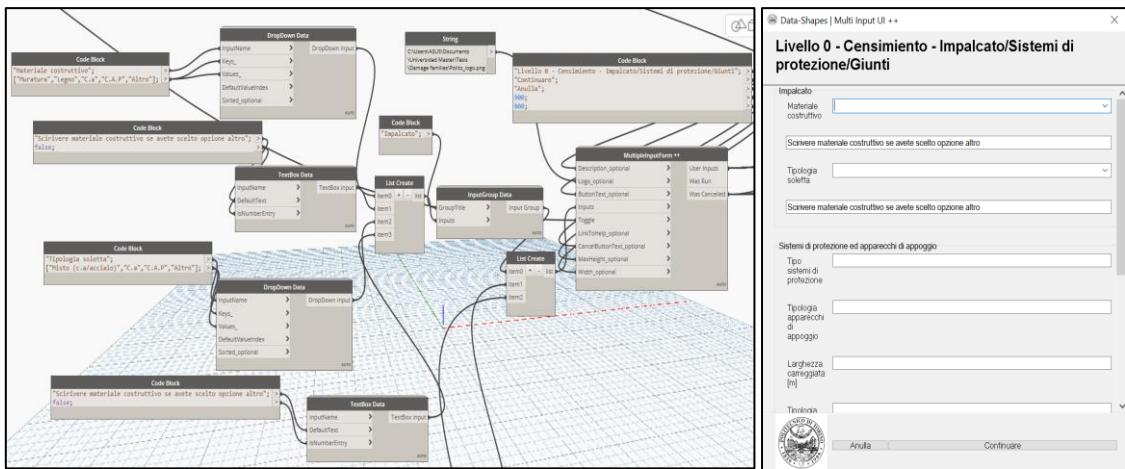
Figure 64. User interface and code for damage inspection - Level 0 -Bridge elements - Window 3

- **Level 0 – Part 4 – Past interventions**

Families:

- Censimiento – Manutenzione
- Censimiento – Ispezioni
- Censimiento – Monitoraggio

Information to be recovered

- Information about previous structural actiones
- Information about previous maintenance actions
- Information about previous inspection actions
- Information about previous monitoring actions

Parameters

- Type of structural intervention	- Number of maintenance works	- Inspections results
- Description of structural intervention	- Maintenance dates	- Monitoring works
	- Inspection works	- Monitoring plan
- Maintenance works	- Inspection plan	- Monitoring methodology
	- Number of inspections done.	- Monitoring dates
- Maintenance plan	- Inspections dates	

<u>*Code description*</u>

This user interface was created thanks to the Dynamo package Data Shapes. In this script, three different windows are opened to the technician in order to fill the needed data.

- Window 1: Information about general bridge previous structural interventions is requested. According to the user answer parameters from the family *"Censimiento – Manutenzione"* are filled.
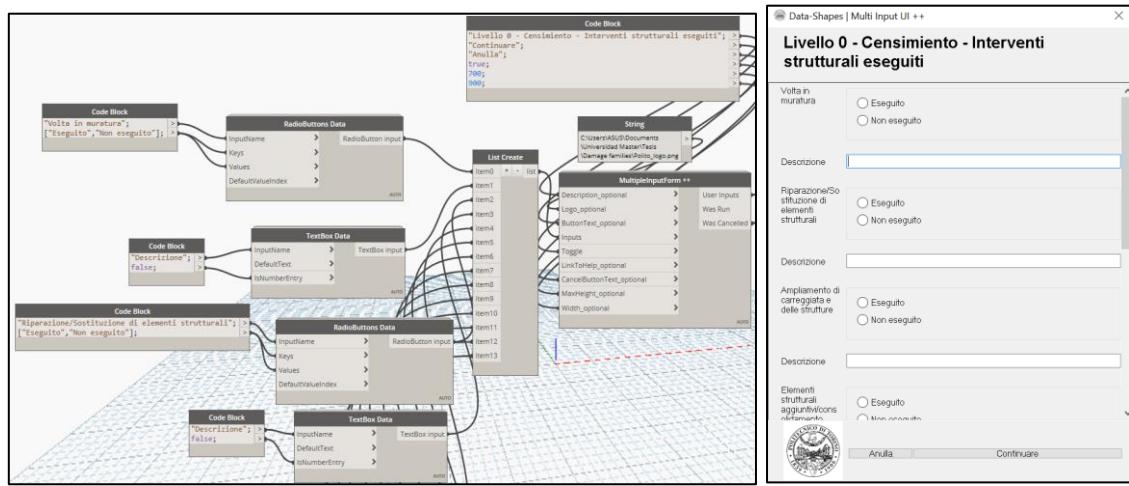
Figure 65. User interface and code for damage inspection - Level 0 -Past interventions- Window 1

- Window 2: Information about bridge previous maintenance interventions is requested. According to the user answer parameters from the family *"Censimiento – Manutenzione"* are filled.
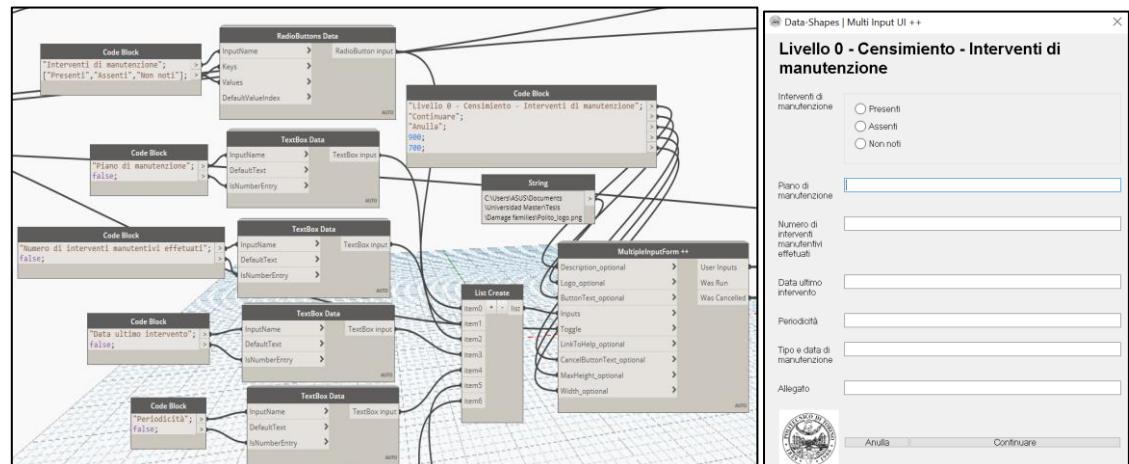
Figure 66. User interface and code for damage inspection - Level 0 -Past interventions- Window 2

- Window 3: Information about bridge previous inspection operations is requested. According to the user answer parameters from the family *"Censimiento – Ispezioni"* are filled.
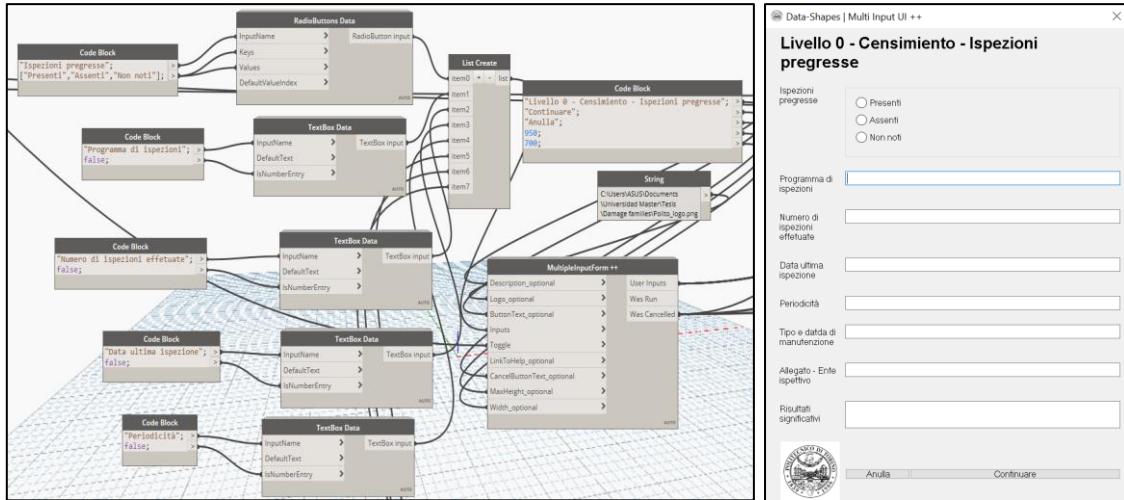
Figure 67. User interface and code for damage inspection - Level 0 -Past interventions- Window 3

- Window 4: Information about bridge previous monitoring is requested. According to the user answer parameters from the family *"Censimiento – Monitoraggio"* are filled.
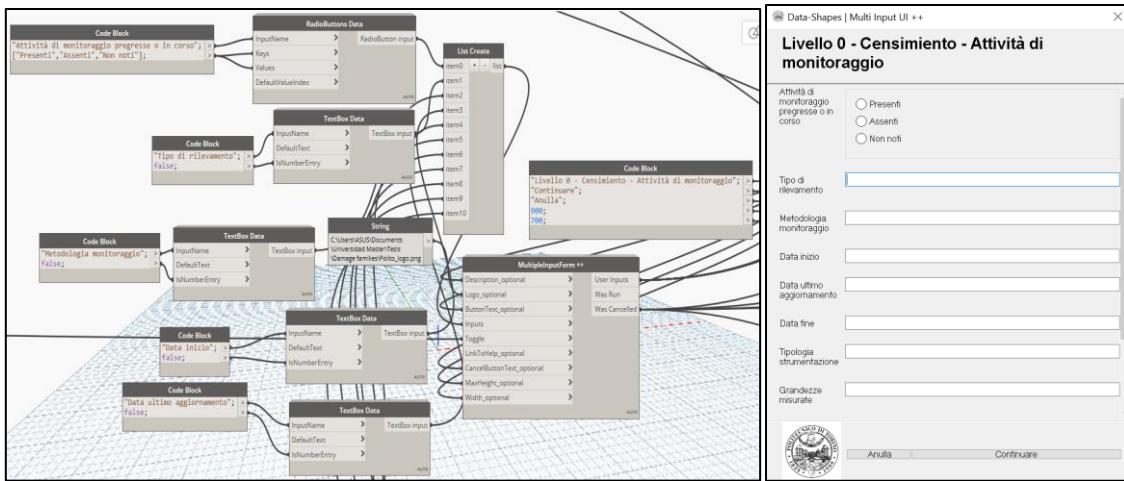
Figure 68. User interface and code for damage inspection - Level 0 -Past interventions- Window 4

- **Level 0 – Part 5 – Traffic and collapse effects**

Families:

- Censimiento – Traffico
- Censimiento – Classi di conseguenza

Information to be recovered

- Information about traffic

- Information about consequences in case of bridge collapse/damage

Parameters

- International route
- Maintenance works
- Average daily traffic on carriageway
- Emergency route
- Number of carriageways
- Number of lanes per carriageway

- Presence of curves
- Average commercial vehicles daily traffic on carriageway
- Average commercial vehicles daily traffic per lane
- Load limitations

- Road alternatives in case of closure
- Alternative route km and time
- Availability of specific traffic studies
- Collapse effects class classification

Code description

This user interface was created thanks to the Dynamo package Data Shapes. In this script, three different windows are opened to the technician in order to fill the needed data.

- Window 1: Information about the bridge road and traffic is requested. According to the user answer parameters from the family *"Censimiento – Traffico"* are filled.
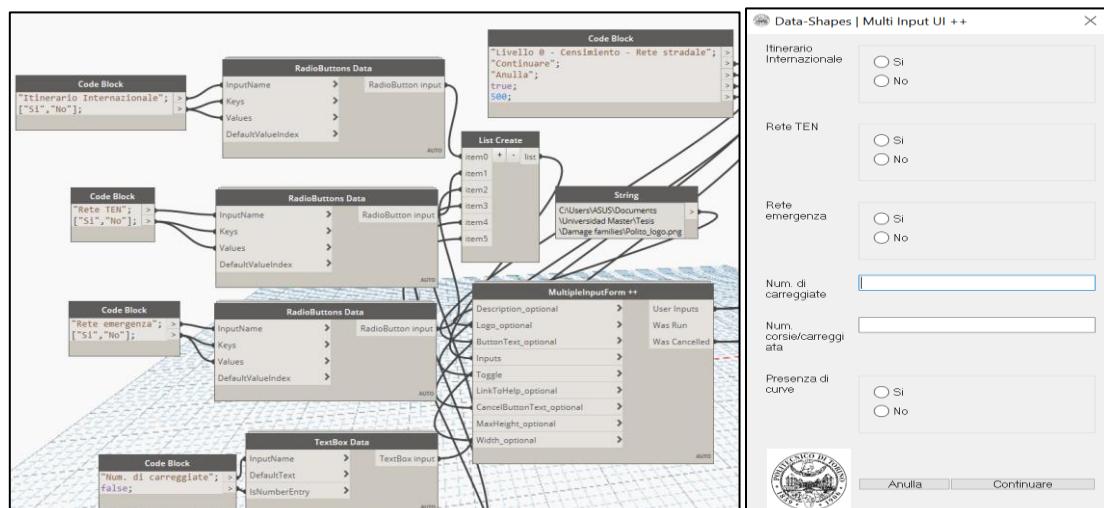
Figure 69. User interface and code for damage inspection - Level 0 -Traffic and collapse effects - Window 1

- Window 2: Information about the bridge road and traffic is requested. According to the user answer parameters from the family *"Censimiento – Traffico"* are filled.
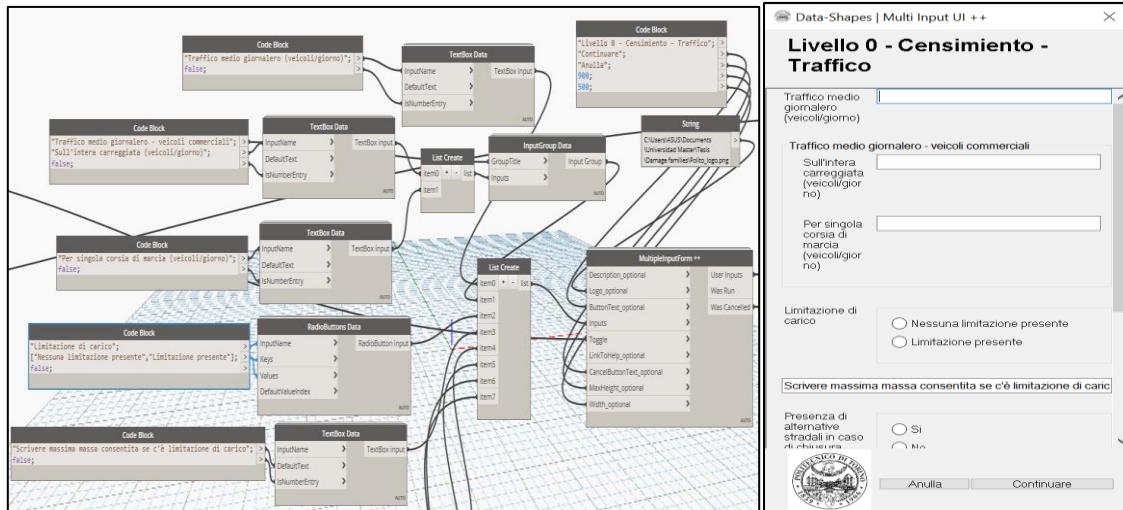
Figure 70. User interface and code for damage inspection - Level 0 -Traffic and collapse effects - Window 2

- Window 3: Information about the bridge consequences in case of damage/collapse is requested. According to the user answer parameters from the family *"Censimiento – Classi di Conseguenza"* are filled.
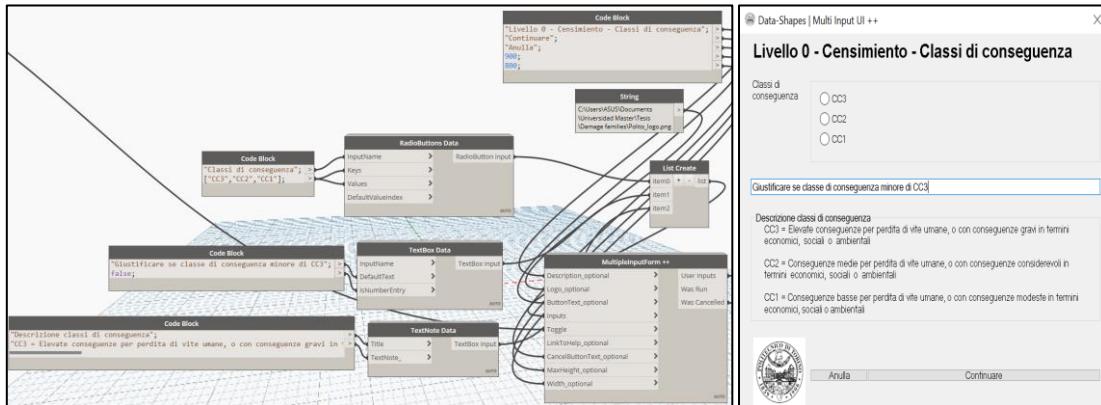
Figure 71. User interface and code for damage inspection - Level 0 -Traffic and collapse effects - Window 3

- **Level 1 – Damage inspections**

Families:

- Abutment – Concrete
- Abutment – Masonry
- Pier – Concrete
- Pier - Steel
- Pier – Masonry
- Truss – concrete

- Truss - masonry
- Bearings
- Joints
- Arcs – Concrete
- Arcs - Steel
- Arcs – Masonry

- Arcs – Wood
- Beams– Concrete
- Beams– Concrete pre-stressed
- Beams – Wood
- Beams – Steel

- Deck – concrete
- Deck – wood
- Additional elements

Information to be recovered

- Information about operator technician, data of damage inspection and element to be inspected
- Information about elements damage according to the Italian Guidelines
- Information about defect weight (G) from 1 to 5. This value is predefined by the guidelines and cannot be changed by the technician. Less severe defects have a weight 1 while more severe damage have a weight of 5 according to the guidelines.
- Information about defect extension (K1). Can have values of 0.2, 0.5 or 1. Generally, 0.2 is applied if the defect is dimly present, 0.5 if is present in more than 50% of surface or 1 if on the complete surface, but its meaning may change depending on the type of damage.
- Information about defect intensity (K2). Can have values of 0.2, 0.5 or 1. Its values changes according to the damage size from 0.2 being the less and 1 being the most. Its meaning varies depending on the type of damage.
- Information about either the damage causes static detrimental in the structure (PS)

Parameters

- Element type
- Technician name
- Inspection Date

- Weight (G)
- Extension (K1)
- Intensity (k1)

- Static detrimental
- Notes

Code description

This user interface was created thanks to the Dynamo package Data Shapes. In this script, three different windows are opened to the technician in order to fill the needed data.

- Window 1: Request the user to select the element to be inspected, name it, put information about inspection date and technician name. According to the user answer, the type of family is selected to be loaded and first parameters are filled.
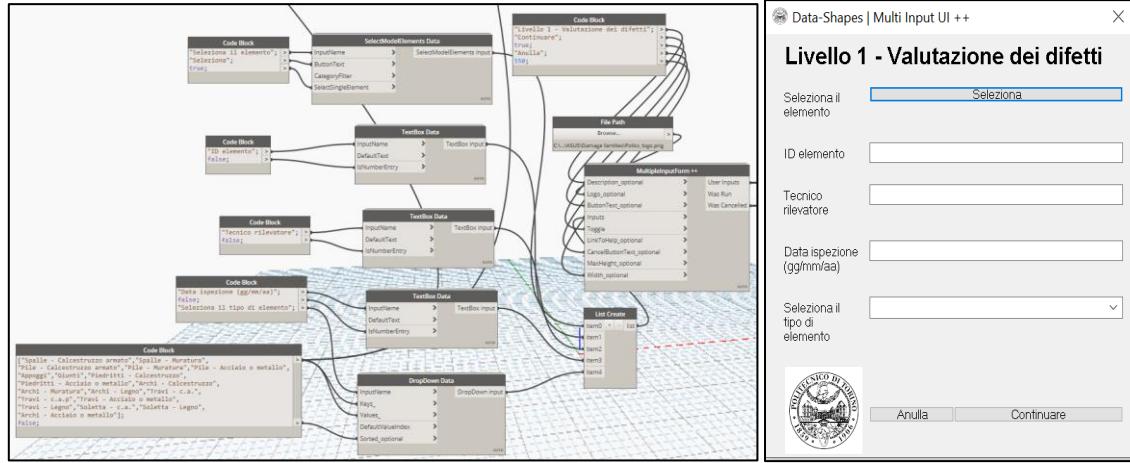
Figure 72. User interface and code for damage inspection - Level 1 -Damage inspection- Window 1

- Window 2: Information about the type of damage is displayed according to the type of element selected by the user in the previous window. The type of damage is requested to the user. According to the user answer parameters from the family uploaded in the first window are filled.
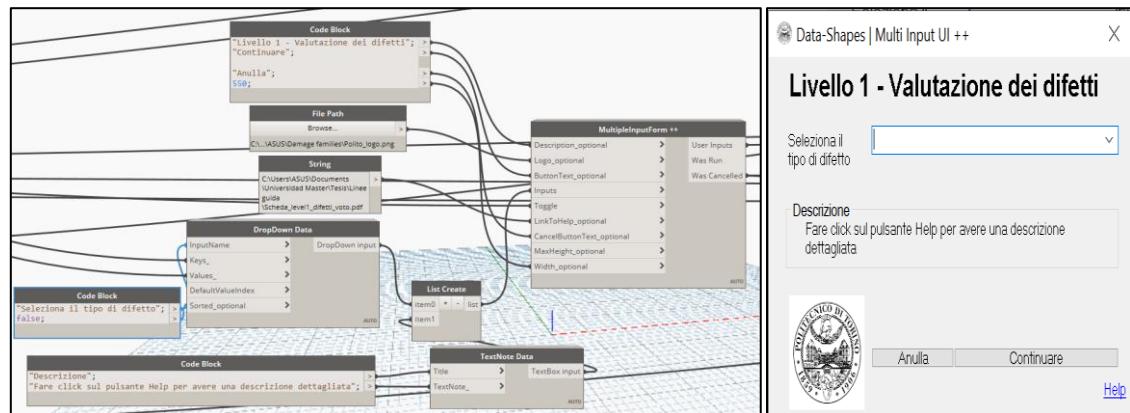
Figure 73. User interface and code for damage inspection - Level 1 -Damage inspection- Window 2

- Window 3: Information about the damage extension, intensity and weather it causes static detrimental is requested to the user. A link of help is provided to connect the software with the Italian Guidelines and know the meaning of the parameters quantities. According to the user answers, parameters from the family uploaded in the first window are filled.
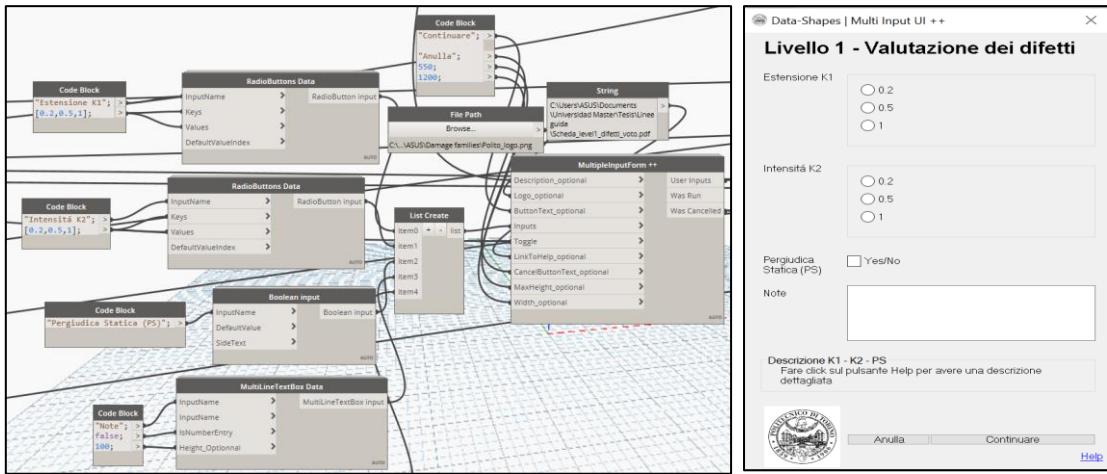
Figure 74. User interface and code for damage inspection - Level 1 -Damage inspection- Window 3

- Window 4: Information about damage position is requested. The label characteristics (Color, radii) are set according to the weight, intensity, and extension of damage set as input in the previous window. The label indicating all the information requested appears inside Revit as an output in the position selected.
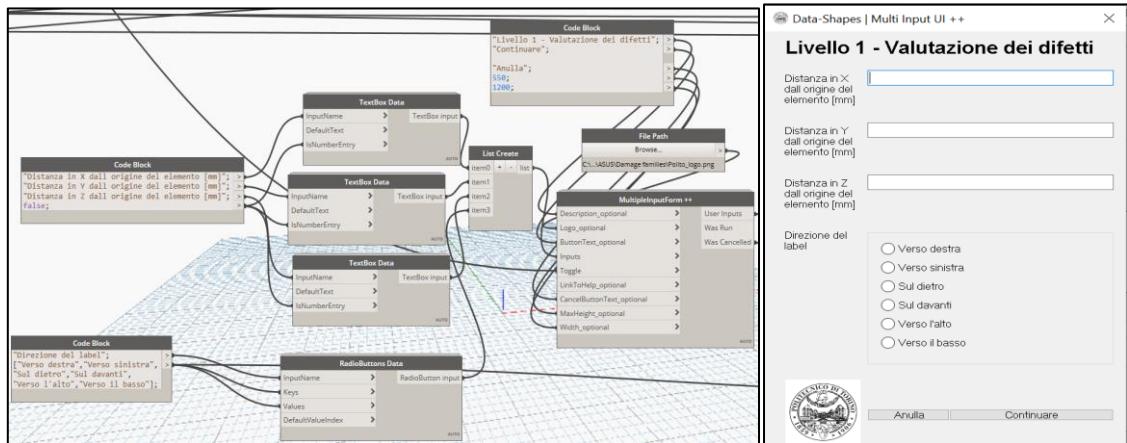
Figure 75. User interface and code for damage inspection - Level 1 -Damage inspection- Window 4

Export level 0 and level 1 to excel sheets

Code description

This user interface was created thanks to the Clockwork and Archilab packages. In this script, no user interface s opened, but automatically as it is run two different excel files are created, one for information of level 0 and one for information of level 1. On this excel files one sheet is created for each family inserted into the project and all the information recollected is displayed.
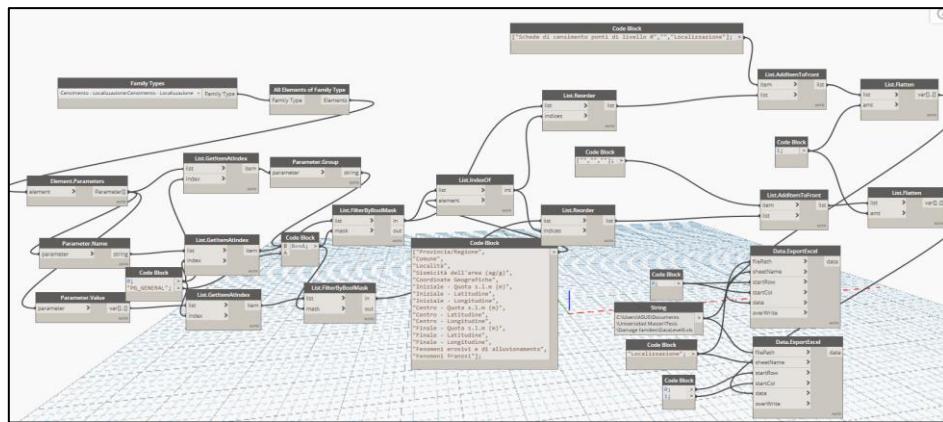
Figure 76. Code for data exportation to excel.

4.2.7 Application of the Italian Guidelines inside the Revit model

Once the user interface was finished, it could be applied to the created model. Both levels from the guidelines were applied to the model in order to show its utility on a real study case, however, as not all of the data required was available at the moment of the creation of the model, some of the parameters were left on blank and other were made up to fill the fields.

Similarly, not all the damage that was present on the bridge was identified and characterized but only a few of the more noticeable damaged parts of the bridge were selected in order to show the application of the interface.
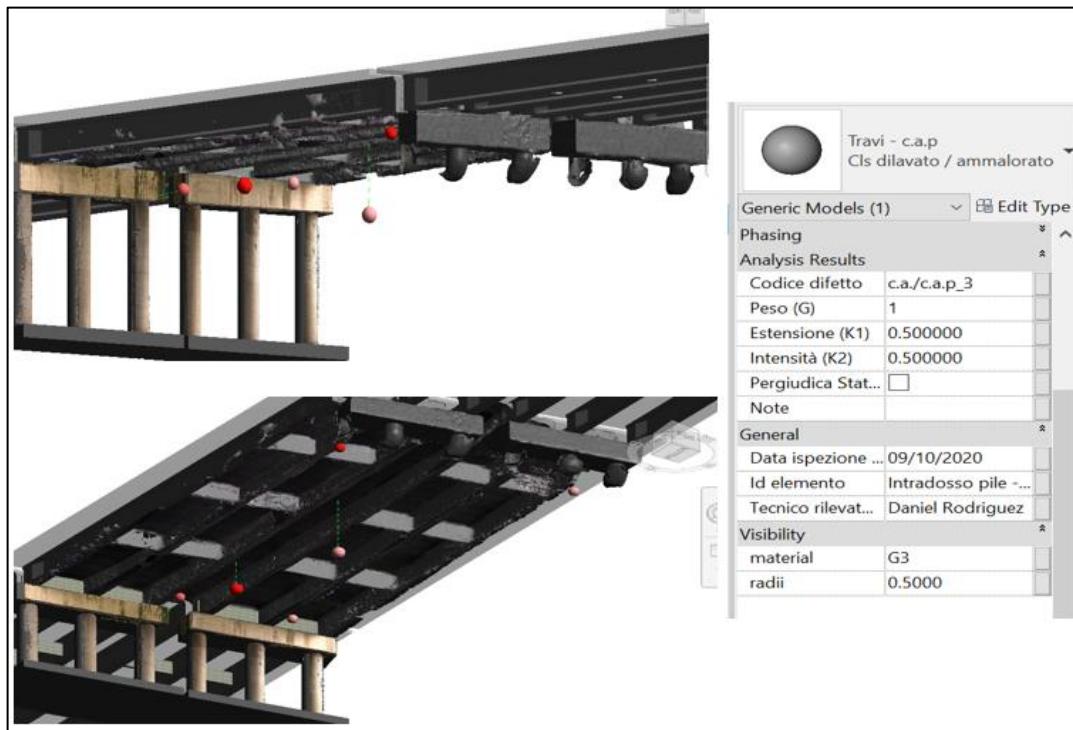
Figure 77. Model after the damage inspection.

Examples of the excel sheets obtained from this brief example are the following ones:

Table 11. Level 0 of the Italian Guidelines applied to the model - part 1.

Informazione iniziale	
Strada di appartenenza	RA10 - RACCORDO AUTOSTRADALE TORINO - AEROPORTO DI CASELLE
Nome Ponte/Viadotto	STURA 43178 43170 Alice
Codice IOP	STSS0010PN094PKEPN
Progressiva km (Iniziale - Finale)	-
Localizzazione	
Provincia/Regione	Torino / Piemonte
Comune	Torino
Località	Villaretto
Sismicità dell'area (ag/g)	0.015
Coordinate Geografiche	ETRF2000
Iniziale - Quota s.l.m (m)	-
Iniziale - Latitudine	-
Iniziale - Longitudine	-
Centro - Quota s.l.m (m)	-
Centro - Latitudine	-
Centro - Longitudine	-
Finale - Quota s.l.m (m)	-
Finale - Latitudine	-
Finale - Longitudine	-
Fenomeni erosivi e di alluvionamento	Assenti
Fenomeni franosi	Da verificare

Table 12. Level 0 of the Italian Guidelines applied to the model - part 2.

Rete e Traffico	
Itinerario internazionale	Si
Rete TEN	Si
Rete emergenza	Si
Num. di carreggiate	2
Num. corsie/carreggiata	2
Presenza di curve	No
Traffico medio giornalero (veicoli/giorno)	-
Traffico medio giornalero - veicoli commerciali sull'intera carreggiata (veicoli/giorno)	-
Traffico medio giornalero - veicoli commerciali per singola corsia di marcia (veicoli/giorno)	-
Limitazione di carico	Nessuna limitazione presente
Presenza di alternative stradali in caso di chiusure	Si
Durata deviazione	-
Categoria del percorso alternativo individuato	-
Disponibilità di studi trasportistici specifici	No
Classe di conseguenza	CC3

Table 13. Level 0 of the Italian Guidelines applied to the model - part 3.

Informazione generali	
Proprietario	ANAS S.p.A
Concessionario	ANAS S.p.A
Ente vigilante	ANAS S.p.A
Anno di costruzione/ristrutturazione - ultimo	-
Anno di costruzione/ristrutturazione - event	-
Dati di progetto	
Progettista	-
Norma di progetto	NTC
Ente approvatore	-
Anno di progettazione - Data inizio	-
Anno di progettazione - Data fine	-
Anno di progettazione - Data approvazione	-
Informazione generali	
Stato dell'opera	Pienamente agibile
Tipo di collegamento	Ponte su corso d'acqua - Reticolo principale
Classificazione d'uso stradale	Strada extraurbana secondaria
Morfologia del sito	Pianura
Caratteristiche geometriche	
Luce complessiva (Estesa) (m)	160
Larghezza totale impalcato (m)	140
Num. campanate	5
Luce campanate	30
Tracciato	Rettilineo
Tipologia strutturale	Travate appoggiate

Table 14. Level 0 of the Italian Guidelines applied to the model - part 4.

Spalle	
Tipologia spalla iniziale	Muro a parete - Calcestruzzo armato
Fondazioni spalla iniziale	-
Tipologia spalla finale	Muro a parete - Calcestruzzo armato
Fondazioni spalla finale	-
Pile	
Materiale costruttivo	C.a
Tipologia sezione	Fusto parete piena + Pulvino
Tipologia fondazioni	-
Altezza pile (m)	Variable
Geometria sezione	Cerchio
Numero fondazioni	-
Evoluzione eventuale rispetto al fondo alveo	-
Impalcato	
Materiale costruttivo	C.a
Tipologia soletta	C.a
Sistemi di protezione ed apparecchi di appoggio	
Tipo sistemi di protezione	H1
Tipologia apparecchi di appoggio	-
Larghezza carreggiata (m)	12
Tipologia dispositivi antisismici	-
Giunti	
Tipologia giunti	Giunta Elastometrica - Epoxy
Lunghezza giunto spalla (m)	-
Numero totale giunti	2
Lunghezza giunto pila (m)	-

Table 15. Level 0 of the Italian Guidelines applied to the model - part 5.

Interventi strutturali eseguiti	
Volta in muratura	Non eseguito
Riparazione/Sostituzione di elementi strutturali	Non eseguito
Ampliamento di carreggiata e delle strutture	Non eseguito
Elementi strutturali aggiuntivi/consolidamento	Non eseguito
Interventi di carattere geotecnico in fondazione e-o in corrispondenza delle spalle	Non eseguito
Interventi di mitigazione/protezione dall'erosione di spalle e pile	Non eseguito
Altro	Non eseguito
Interventi di manutenzione	Non noti
Piano/Programma	-
Numero di interventi/ispezioni effetuati	-
Data ultimo intervento/ispezione	-
Periodicità	-
Tipo e data di manutenzione/ispezione	-
Allegato	-
Ispezione pregresse	Presenti
Piano/Programma	ANAS
Numero di interventi/ispezioni effetuati	-
Data ultimo intervento/ispezione	-
Periodicità	3 al anno
Tipo e data di manutenzione/ispezione	-
Allegato	-
Risultati ispezioni/monitoraggio	-
Attività di monitoraggio pregresse o in corso	Presenti
Tipo di rilevamento	Sensori - SYSDEV SHBOX
Metodologia monitoraggio	Accelerometro
Data inizio	-
Data ultimo aggiornamento	-
Data fine	-
Tipologia strumentazione	-
Grandezze misurate	-
Risultati ispezioni/monitoraggio	-
Livello alerta	-
Documentazione relativa	

Table 16. Level 1 of the Italian Guidelines applied to the model.

Travi - c.a		Travi - c.a.p.	
		Id elemento	Intradosso pile - Campata 1
Id elemento	Pulvino 1	Codice difetto	c.a./c.a.p_1
Codice difetto	c.a./c.a.p_3	Difetto	Macchie di umidità passiva
Difetto	Cls dilavato / ammalorato	Data ispezione (gg/mm/aa)	10/09/2020
Data ispezione (gg/mm/aa)	10/09/2020	Peso (G)	1
Peso (G)	3	Estensione (K1)	0.2
Estensione (K1)	0.5	Intensità (K2)	0.5
Intensità (K2)	1	Pergiudica Statica (PS)	No
Pergiudica Statica (PS)	No	Note	
Note	Da verificare	Tecnico rilevatore	Daniel Rodriguez
Tecnico rilevatore	Daniel Rodriguez		
		Id elemento	Intradosso pile - Campata 1
Id elemento	Pulvino 2	Codice difetto	c.a./c.a.p_3
Codice difetto	c.a./c.a.p_1	Difetto	Cls dilavato / ammalorato
Difetto	Macchie di umidità passiva	Data ispezione (gg/mm/aa)	10/09/2020
Data ispezione (gg/mm/aa)	10/09/2020	Peso (G)	1
Peso (G)	1	Estensione (K1)	0.5
Estensione (K1)	0.2	Intensità (K2)	0.5
Intensità (K2)	0.2	Pergiudica Statica (PS)	No
Pergiudica Statica (PS)	No	Note	
Note		Tecnico rilevatore	Daniel Rodriguez
Tecnico rilevatore	Daniel Rodriguez		
Id elemento	Pulvino 3		
Codice difetto	c.a./c.a.p_11		
Difetto	Arm. Scoperta / ossidata testate		
Data ispezione (gg/mm/aa)	10/09/2020		
Peso (G)	2		
Estensione (K1)	0.2		
Intensità (K2)	0.2		
Pergiudica Statica (PS)	No		
Note			
Tecnico rilevatore	Daniel Rodriguez		
Id elemento	Pulvino 4		
Codice difetto	c.a./c.a.p_1		
Difetto	Macchie di umidità passiva		
Data ispezione (gg/mm/aa)	10/09/2020		
Peso (G)	1		
Estensione (K1)	0.5		
Intensità (K2)	0.2		
Pergiudica Statica (PS)	No		
Note	Da verificare		
Tecnico rilevatore	Daniel Rodriguez		

Chapter 5: Results, Conclusions and future work

5.1 Results

5.1.1   Introduction

As it was specified on section 2, the aim of this research was to demonstrate and test the value of remote sensing methodologies for BIM modelation and likewise the use of BIM for SHM with its practical application in real study cases.

On this sense, in the first study case, Largo Grosseto overpass, as the SHM data was already recovered a methodology in terms of passing SHM information from traditional means to BIM methodology was first tested. Moreover, on this study case two methodologies were tried for BIM modelation: Parametric modelation and direct modelation from photogrammetry.

On the other hand, for the second study case, The Stura Bridge, there was no SHM data previously recovered, so a completely new survey and inspection was done. On this study case, the process of surveying and analysis of information recovered was implemented. Additionally, the modelation on BIM software was completely done through a semi-direct importation from remote sensing software and a user interface was created in order to produce the damage inspection and SHM data visualization directly on the BIM software.

5.1.2   Results in terms of BIM modelation for SHM purposes: Parametric modeling vs Remote sensing importation approach

As it was seen on previous sections, different options in terms of modeling can be applied on BIM software for SHM purposes. On this sense, in this research the parametric modeling and the remote sensing approach (Semi-direct importation) were tested. The results can be described as follows:

- Parametric modeling:

One of the main advantages of BIM software is its capability to create almost any 3D geometry from zero without being limited of pre-disposed shapes. On this sense, Revit offers a great solution for parametric modeling as it offers a vast quantity of families options to draw a 3D geometry but at the same time is not limited to pre-established families, so any type of element can be created from templates such us "Generic Model"

or "Generic mass". On this sense, for the Largo Grosseto Bridge, the beams were modeled as "Structural framing" but the damage information was modeled as "Generic model" and all the respective information could be added to both families.

Then, the biggest advantage of parametric modeling is its easiness in creation, control and editing of any type of basic 3D shape. With simple tools, such as "*extrude*" or "*revolve*", basically any type of simple shape can be rapidly created and visualized on 3D. Moreover with the creation and use of parameters, this 3D shapes can be edited without the need of enter again into the geometry editor inside the family, which allows the rapid creation of many elements of variable geometry from a single modeled family. However, on the context of SHM, where many details should be present in the model and a high level of fidelity with respect to the reality should be present, this methodology may result inadequate.

The parametric modeling offers the possibility of rapid creation of simple shapes and its control, however, when dealing with real objects, where complex shapes should be accompanied by details because of imperfections, damage and textures, this methodology may result tedious and insufficient. Modeling all of the details from imperfections, as parametric drawings results in an impossible task, so all surfaces in the model remain plane, contrary of how they are in reality. Additionally, texture results in parametric modeling may look unrealistic, as they can only be created from generic colors and generic patterns, thus, surface damage information is lost. On this research, for the Largo Grosseto Bridge the damage information was already recovered and modeled in AutoCAD software so it was displayed in the model through the creation and inclusion of new damage family, however, this is not the case of the vast majority of bridges, so in any other case this information would be lost.

A better result of parametric modeling may result by also applying a merging the remote sense technologies on this methodology. This is, creating a point-cloud from a photogrammetric/laser scanner model and using it to compare it with the parametric family created, as it was done for the Largo Grosseto Bridge. This methodology helps to improve the results of the parametric model in terms of scale fitting, size and detailing, however, still does not help to include to the model information about surface and texture details and imperfections.

A final big advantage that was seen from this type of methodology was the usefulness of the interoperability between software. On this study case, the information about measurements of beams and damage of the structures was already recovered on AutoCAD drawings, so the passage of information resulted easy and the creation of the damage families turned out to be just a process of data importation and creation of parameters to include information. This is a great advantage for the creation of a unique database, because information from many types of documents may be rapidly included into a single model. However, on this case all of the information about damage was previously recovered and modeled on AutoCAD, so even if this last step of importation to create a unique database may result rapid and easy, a vast work in terms of manual data recovery is needed initially.

- <u>Remote sensing approach (Semi-direct modeling)</u>

With respect to the photogrammetric/Laser scanner semi-direct approach of modeling in BIM software, the result in terms of model detail and quality is much better than the results with parametric modelation. The results obtained from both study cases with this methodology allowed a visualization of data in the BIM platform that allowed a correct inspection and characterization of damage for SHM purposes. Additionally, the capacity of this methodology to maintain real surface and shape consistency make each model highly precise, unique and reliable to the object it represents.

In fact, the level of detail of the 3D model obtained is so good that future work and development from this model can be expected. For example, ideas in terms of automatized image processing with machine learning technologies is a logical step in which this type of model may proceed for automatic identification and characterization of the present damage.

In addition, as it was shown on the Stura Bridge, the methodology of survey for this type of approach has great advantages with respect to traditional survey methods as it provides an easy and rapid solution to collect a large amount of data. Then, mixing this data with information from a topographic survey, the scale, orientation and in general precision of the model can be assured. A remote sensing survey also allows a complete survey of the structure, reaching many areas and angles that traditional survey methodology would not be able to reach. This aspect was specially shown on the Stura Bridge survey, where details from areas difficult to reach like the intrados could be

obtained and included in the model. Moreover, these difficult to reach areas can later on be inspected and analyzed directly through the 3D model of structures, taking into account the high precision of the object created.

Nonetheless, the velocity and easiness of this type of survey contrasts with the large quantity of operations that need to be applied to the product obtained. As this methodology is not a "smart survey", many data that should not need to be included in the model is included (E.g. Digital noise) and some other information that should be included is not automatically included. This problem consequently produces the necessity a great number of operation to process the data obtained. As it was shown in both study cases, operations of georefernciating the model, separation of elements, decimating the cloud, cleaning the digital noise, setting into scale, repairing the imperfections, layering and compression were needed. Taking into account the big size and computationally demanding output produced by this methodology, this obligation of high processing the information obtained results costly not only in terms of time-consuming, but also in terms of technology resources.

Considering the vast quantity of information recovered with the remote sensing approach, the specifications of the technologic resources where the data is processed should be also taken into consideration. A precise estimation of the correct hardware characteristics needed to manipulate the information should be made, otherwise, simple necessary operations to be applied to the products may turn out to be excessively time demanding or even impossible.

Moreover, the final 3D object created is highly dependent on the algorithm and parameters chosen for the mesh reconstruction and on the quality of the point cloud from which it is produced. This limitation may induce in errors in the final triangulated mesh produced if digital noise is still present in the final point cloud, or the complete geometry of the element cannot be obtained from the point cloud. Biases in the mesh like bumps or voids that may alter the element geometry may be present in the final product, which can ultimately produce errors in the damage characterization.

However, the biggest disadvantage found in this methodology was the lack of interoperability between photogrammetry software and BIM software. As no direct passage from a 3D triangulated mesh software to a BIM platform exists, a semi-direct passage needed to be ideated by using several software. On this thesis, two different paths

were explored for this semi-direct importation: The usage of Autodesk Dynamo with the package *Mesh Toolkit* and the usage of the format *.DXF* for the export/import process. The usage of the Dynamo complement to import meshes showed to be particularly computationally heavy for Revit, so only extremely decimated meshes (and consequentently inaccurate) could be imported. Moreover, this passage did not transmit any texture to the Revit environment. Due to these limitations, the second option was chosen for the modelation.

The fact that the solution found implied an exportation format from the mesh editing software to the BIM software in a *.DXF* format (a format that is intended for AutoCAD and not for Revit) exemplifies how little interoperability between software exists on these cases. This semi-direct passage causes a lost in information that affected the velocity and quality of the results obtained. In this case, the texture/color information was lost for both study cases through this passage. Furthermore, the imported object is not subdivided into elements that are editable in Revit, as it is an imported "block" in the BIM software. At the end, the problem of information loss was solved separating each face of the 3D object into layers on MeshLab and then creating a new material for each planar surface of the elements in Revit. However, this solution implied additional manual operations to be applied to the mesh, and even the use of additional software for picture editing to create the materials on Revit. At the end, a decent result for SHM analysis is obtained, but the quality of the final product is not as good as the original one.

5.1.3   Results for SHM data management and visualization in BIM software

As it was exposed in the introductory chapters, BIM software has the great advantage of allowing the creation of a unique database with information of many different sources and types reunited together. This statement was proved especially with the creation of the user interface program with Dynamo. As it was seen, this user interface allowed the automatic inclusion into the project of a large number of data, not necessarily related one to the other, and coming from of different types of sources. Then, when the data was already inserted into the model it could be easily visualized, managed and even exported into external tools such as Excel.

Additionally, this aspect of the utility of BIM software to create a unique SHM database was also exemplified on the transmission of information from traditional means to Revit for the Largo Grosseto Overpass. On the procedure of creation of the parametric

families of this study case, all the information was initially recovered in PDF, excel and AutoCAD drawings. With the importation done to create the beams and damage families and then the merging of these two families into a unique project a unique SHM database could be created. The fact of having all of the information recovered in a single project file allows a better understanding and visualization of the project information. Moreover, the inclusion of "dummy" damage to test the over-time utility of the model proved the easiness in the management and actualization of the model.

On the other hand, the inclusion of 3D objects from remote sensing technologies into the Revit model proved the capability of the model to recover information not only in text format but also visual. This visual information attested such quality that allowed a SHM visual inspection directly on Revit. This represents a great advantage for SHM because contrary of normal inspection sheets allow all the information (Visual and text) to be recovered in a single 3D model.

Finally, the usage of dynamo demonstrated that an automated and standardized procedure for inspection could be realized directly on BIM software. In this case, the user interface created allowed the complete recreation of the level 0 and level 1 of the new Italian guidelines for bridge inspection and monitoring. This user interface illustrates an example of how data of many different types can be inserted into Revit in an easy and fast manner. Moreover, its user-friendly platform allows a technician without any expertise in programming or in BIM technologies to realize the bridge inspection directly on the model, and save the data in a unique file.

5.2 Conclusions

The present thesis work aimed to test the utility of remote sensing techniques for BIM modelation and likewise the usage of BIM methodologies for SHM. In order to test these characteristics two study cases were analyzed: Largo Grosseto Overpass and the Stura River Bridge on the motorway connection RA10. After obtaining the results of these two study cases, the following conclusions can be stablished:

- The usage of BIM methodologies to create a unique SHM database results helpful and produces an improvement in the data storage, visualization and management. The capability of BIM software, such us Revit, to combine data from many different sources, display text and graphical information in a single environment and create

models that can be actualized over-time result in a perfect match for its usage for SHM purposes.

- The usage of remote sensing for BIM modeling could produce models of enormous quality; however, the lack of interoperability between photogrammetry and BIM software does not allow achieving a standard methodology for a direct modelation. Other type of procedures, different from the ones tried on this thesis work, could be proved in order to import a triangulated mesh into BIM environment, however, the fact that there is not even a generalized workflow inside the software houses produces enormous disadvantages for its application as a standard in other study cases.

- The usage of remote sensing technologies as a method of survey allows an easy, low cost and fast solution to create a realistic representation of the reality. However, as this is not a "smart survey methodology", the velocity and easiness of the survey contrasts with the high number of manual operations that should be applied to the output obtained. These high numbers of operations may turn out to be extremely time-consuming and computationally demanding.

- The usage of photogrammetry and laser scanner as methodologies for creating of 3D digital objects produces an output with excellent characteristics in terms of quality and level of detail. The quality of the output obtained from this process is of such greatness that procedures of visual damage inspection and characterization may be applied directly on the model itself instead of on the real object on field.

- An accurate analysis about the computational resources available should be made prior any remote sensing survey is performed. Considering the quantity of information recovered with this type of methodologies, the technological resources should be an input data to take into consideration when deciding of how many data should be recovered and what type of operations should be applied to process this information.

- The help of visual programming tools, such as Dynamo, inside BIM software produces great results to automatize and standardize processes of data insertion, editing and exportation. Moreover, its ability to access the Revit API to create a user-interface that assists and guide the user in the process of data insertion allows that

even a person with no expertise in BIM software can realize this process. On this sense, for SHM purposes, this user-interface results extremely useful, as a technician can realize the damage visual inspection directly on the Revit software and export the results into excel sheets.

- The final quality of the triangulated mesh created by the remote sense technologies is highly dependent on the parameters chosen for the mesh reconstruction and on the quality of the point cloud from where it is produced. This condition implies that the completeness of the survey in order to capture the subject geometry and the automatic/manual operations done during the processing of the obtained data should be made with extremely precaution in order to avoid error on the final product.

- The methodologies of photogrammetric survey using UAVs with camera pointed upwards instead of downwards is possible and may produce optimal results. During this thesis work, the photogrammetric survey for the Stura Bridge was realized with an experimental, modified drone where the camera was placed in a 45° angle pointing upwards instead of downwards as it normally occurs. The results obtained show that this type of survey is possible and may be of great importance for analyzing a broad type of structures such as bridges or tunnels.

5.3 Future work and recommendations

As the experiences of this thesis work have showed, there are plenty of fields of actions in order to continue with future research and work in both remote sensing inclusion on BIM platform and usage of BIM methodology for SHM purposes.

Firstly, the development of a methodology and workflow for direct modeling of 3D objects from photogrammetry/Laser scanner in BIM software is still pending. The fact that this interoperability problems between these two types of software still exists make this passage of information tedious and not feasible. Future research on different methodologies to reach this direct modeling is needed as the remote sensing output have shown a huge advantages in terms of model quality and level of detail and may produce an important revolution for the creation of As-is models and in general on the field of HBIM.

Second, the photogrammetric/Laser scanner output has demonstrated that the level of detail of the 3D model obtained is of such good quality that the visual damage inspection

can be directly applied on the model instead that on the field. On this sense, future work is expected in terms of automatized image processing with artificial intelligence technologies for damage detection and characterization. This is a logical future development for this workflow as it would avoid the possibilities of human errors and ensure the accuracy of damage.

Moreover, the utility of visual programming platforms such as Dynamo inside the BIM environment have proven to be an important tool for data collecting and management. On this research the level 0 and level 1 of the new Italian guidelines for bridge inspection monitoring were recreated by programming a user-interface; however, this same work can be also done to include information from all the other levels from the guideline, so a complete inspection and characterization of the bridge can be realized directly on the BIM platform.

Finally, the UAV photogrammetric survey made on the Stura bridge study case shows that the possibility of a photogrammetry with the camera on an inverted position is possible to analyze structures such as bridges. This type of survey is an innovative fast solution for data acquisition, reaching angles and sections of structures that otherwise may not be possible to reach. Further work on this type of survey is needed so that it can be used as a standardized procedure in remote sensing surveys.

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