DESDEMONA Achievments

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Abstract. DESDEMONA achievements constitute a series of steps beyond the status of knowledge at the EU funded project starting on 1st June 2018, in the development of novel design methods, systems, procedure and technical solution, to integrate sensing and automation technologies for the purpose of self-inspection and self-monitoring of steel structures. The obtained results will lead to an increment of the service life of existing and new steel civil and industrial infrastructure and to a decrease in the cost associated to inspections, improving human activities performed in difficult conditions, safety and workers' potential by the use of advanced tools. The research succeeded to expand new high-quality standard and practices for steel structure inspection and maintenance through the interrelated development of the following actions: i) steel structure geometry and condition virtualization through data fusion of image processing, thermography and vibration measurements; ii) developing of procedure for steel defect detection by robotic and automatic systems such as Cable-Driven Parallel Manipulators (CDPM), Unmanned Aerial Vehicles (UAV), Wall Climbing Drone (WCD), Cable Climbing Robot (CCR) and Wheeled Robot (WR) iii) embedding sensor systems to revalorize and transform steel elements and structures into self-diagnostic (smart) elements and materials even through nanotechnologies, iv) realizing an experimental lab-based apparatus and a series of case studies inspected by intelligent and robotic systems. The project outcomes are determining an impact on the reduction of the cost of steel structures inspection and maintenance and on the increase of user safety and comfort in industrial and civil environment.

Keywords. Structural Health Monitoring, Robotics, Steel Structures

1. Introduction

DESDEMONA - DEtection of Steel DEfects by Enhanced MONitoring and Automated procedure for self-inspection and maintenance is the title of a European Project funded by 2017 RFCS call under contract no 800687. The project initially planned for 36 months starting on 1st June 2018, due to COVID pandemic, went ahead for 45 months up to end of February 2022.

Even if the integration of sensing and automation technologies in several engineering fields has reached a great level of development, for the steel constructions significant enhancements can be pursued extending the reached results adopting new approaches in the management and maintenance of new and existing steel structures. The DESDEMONA project succeeded to produce a breakthrough in the scientific and technological knowledge for the monitoring of defects and damages of steel constructions through affordable solutions adding specific novel benefits with respect to the closely related financed RTD projects and the current research state-of-art.

The project has been organized through 7 WPs which are strictly connected as explained in Figure 1. Each WP foresees the production of 4 Deliverables in average indeed the total number of Deliverables is 28 plus the final report which bring the total to 29 Deliverables.

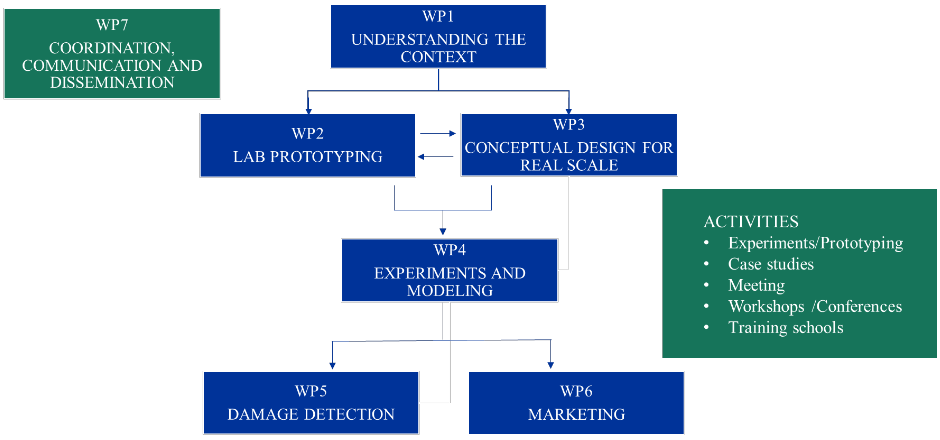

Figure 1. Organization of activities in WPs for the DESDEMONA project

2. Objectives

In the following, the main objectives of DESDEMONA project are summarized and the work carried out to achieve project objectives is here described.

Objective 1: *Development of a catalogue of suitable solutions for innovative steel structures integrated with sensing and monitoring for self-evaluation using automatic and robotic systems embedded in steel structural components, such as for example cable-driven manipulators to drive micro e macro sensing equipment.*

Several solutions for automatic inspection were developed and the results have been disseminated through the DESDEMONA web site in which in the section activities a summary is reported (https://www.desdemonaproject.eu/activities/). In particular, three sections are presented on the web site:

i) Automatic inspection and maintenance systems
ii) Steel structure defects
iii) Automatic solutions for defect identification

Objective 2: *Design and development of a lab experimental apparatus as a paradigmatic integrated system to demonstrate the feasibility of producing novel steel structures thought at the design stage with an equipment of low-cost automatic systems to monitor deterioration and damage evolution and eventually able to actuate self-maintenance actions.*

Specific design or modification of robotic and automatic prototypes, and sensorization planning and experimental testing on novel solutions of robotic and automatic prototypes for inspections were performed [29-31]:

i) Design of automatic prototypes and sensorization planning together with design drawings for prototypes on:
   - Cable-Driven Parallel Manipulator (CDPM)

- Unmanned Aerial Vehicle (UAV)
- Wall Climbing Drone (WCD)
- Cable Climbing Robot (CCR)
- Wheeled Robot (WR)

In the first case, a study on exact positioning were conducted developing a full analytical model used for the direct and inverse kinematics [4, 26]. Specific features of the different solutions were illustrated, and the realization of the prototype has permitted to deal with technical problems which have been solved with original solutions bringing the development up to the presentation of a patent. [5-7].

ii) Realization and experimental testing in prototyping three of the selected robotic solutions: a cable-driven robot for automated inspection of the downer part of decks of bridges; a wheeled robot for automated inspection of horizontal flat of structures; a hybrid drone to place payload (as sensors). The cable-driven robot for decks inspection was improved and a novel proposal was designed, built and validated. The experimental results presented demonstrated that the three proposals can be applied for the real cases of study.

Objective 3: *Design and development of real case studies of a novel or existing steel structures equipped by an automatic and robotic embedded inspection system.*

<u>Description of automated systems for inspection</u>

Insights about real scale design robotic solutions that can be used for the inspection of bridges were given. However, feasible and engineering solutions were presented and discussed, namely a cable driven parallel manipulator (CDPM) designed to be integrated in two selected cases study of the DESDEMONA project. The mechanical design with constructive details was illustrated and described. In particular, the CDPM was designed, and it is under construction to be mounted together with a classical monitoring system. First experimental tests referring to accelerometers were already carried out for the cases of study.

<u>Procedures for deployment of automated systems in existing steel structures</u>

A summary of the automatic inspection and maintenance systems proposed in DESDEMONA project was given together with the description of the automated inspection procedures that can be implemented through the use of the robotized systems proposed. The inspection procedure is organized in 4 phases. Phase 1 deals with image or video capturing and it includes planning and access path for automatic inspection. The second phase consists of the creation of a Contextual interface and the use of a database of structural elements and defects. The third phase deals with experimental calibration and the last phase deals with the defect analysis that requires the recognition and identification of both the observed object with respect to the background and the specific defect identification in the observed object [12].

Objective 4: *Development of data fusion techniques for damage detection through integration of image/video processing and vibration measurements.*

<u>Vibration-based damage detection</u>

Long-term tracking of modal parameters of monitored structures was focused. A robust software for vibration-based damage detection and a monitoring framework for damage detection were developed.

i) A software package that integrates most of the presented algorithms was developed for the management and processing of the large amounts of data collected by permanent dynamic monitoring systems. The developed monitoring software was named DynaMo, which stands for DYNAmic MOnitoring. Its main goal is to transform the collected acceleration time series into meaningful information from the structural behaviour point of view.

ii) A monitoring framework for damage detection, its implementation and the validation with monitoring data collected during more than one year was defined. The tools used for the minimization of operational and environmental effects on modal properties were described with reference to two case studies (a cable-stayed bridge and an onshore wind turbine).

<u>Integration of image/video processing and vibration measurements</u>

Two laboratory experimental campaigns and a field experience were carried out to show the potentiality of the vision displacement sensor as vibration measurement.

i) The first laboratory activity validated the potentials of the vision displacement sensor for structural health monitoring (SHM) and investigates on the direct processing of selected pixel brightness time variations for SHM. For both cases, a subspace system identification-based method was used, so that the modal parameters, including the natural frequencies, damping ratios and mode shapes, with uncertainty bounds are estimated within a large range of model orders displayed in a stabilization diagram. The results of laboratory experiments on a cantilever beam structure, excited by a shake table driven piloted in random noise, demonstrated the high accuracy of the vision sensor and so called virtual visual sensor separately [18, 21].

ii) The second laboratory activity aimed to use displacement measurements extracted from images to validate image-based operational modal analysis and damage detection in an instrumented small-scale steel frame structure. Compared to traditional sensors, such as accelerometers or velocimeters, the use of high-speed cameras for data acquisition allows the number of measurements points to be significantly increased. This high number of measurement points was exploited to explore different damage detection techniques by using displacement data and modal quantities. Damage localization and intensity were determined through image-based measurements without losing the accuracy obtained with accelerometers and the performance of damage indices was evaluated in relation to the type of measurements [1, 3, 32].

iii) The field experience was carried out on a cable-stayed pedestrian bridge. Vision-based measurements obtained from high-speed camera images were used to extract cables vibrations and to estimate their axial forces. These measurements allowed to identify natural frequencies of loose cables which were not detectable with the accelerometers data [16].

Objective 5: *Development of new models describing the complex behaviour of steel structures and their damages thanks also to fusion of data coming by image processing and acceleration measurements integrated in a Building Information Modelling (BIM) environment*

The research exploited classical procedure of damage detection based on dynamic measurements in conjunction with novel techniques of image processing. The damage detection procedure aims to identify the position, level and extension of the damage due to fatigue and/or corrosion process. The development of new models describing the complex behaviour of steel structures and their damages thanks also to fusion of different data was through four steps described below and showed in Figure 2. Flowchart of steps i, ii, iii of the proposed procedure.

i) The first part of the proposed methodology provides a general model of a plane steel truss that is investigated through a sensitivity analysis to highlight the effects on the main dynamic properties and displacements of different positions, extensions and levels of damage that is modelled as cross section reduction of a single element of the truss. A stiffness matrix of damaged element was derived, implemented within the FEM procedure to obtain a numerical finite element model used to generate a pseudo-experimental data which may represent the dynamic structural response of the damaged truss under white noise, and which are utilized to identify the dynamic characteristics of the damaged structure: natural frequencies, damping coefficients and mode shapes. Finally, to extract and identify the main modal parameters through an Output-Only analysis, the SSI was performed with consequent resolution of the inverse dynamic problem. A damage index was defined to evaluate the Stiffness Reduction Factor SRF through different methods concerning the global analysis. Also, a flexibility-based approach was used on the general model. [20, 23, 24]

ii) In the second part, the analysis concerned the enriched or fine model, and it aims to introduce more parameters in order to better describe the damage, this target is pursued by centring the attention to a real case study that is an historical steel railway bridge located in Spain, the Quisi Bridge. This part consists of two distinct analyses, in the first one, the selected case study was analyzed by means of experimental/numerical analysis. The identification of the structural real dynamic behavior was realized through experimental "in field" tests using ambient vibrations by means of SSI; based on updating procedures it is possible to calibrate the numerical model with respect to the experimental data. The updated model is used to locate the critical connections where fatigue damage could arise, which are then analyzed through local models. The local model is obtained selecting on the updated global model, the critical details most exposed to fatigue problems in order to properly reproduce the local dynamic behavior and to obtain the fatigue resistance of details. The local analysis of connections is performed in order to identify other parameters which can describe the damage and can be utilized at a global scale for the definition of the error function.

iii) The final part of the methodology refers to the image acquisition campaign and processing in order to extract some useful information and to characterize the current health state of joints. The non-destructive tests were carried out through in situ Gamma-rays image acquisition and processing, the results of radiographic tests enrich the description of damage on the local model and these were compared with the results obtained from the local analysis. The final aim of the local analysis is to introduce parameters able to describe damage with high accuracy and on such basis to update the global model.

iv) Building Information Modelling (BIM) environment was used to implement an integrated monitoring in which data are stored in the model and processed for an updating of the mechanical behavior using sensors. This action constituted a novel and updated experience in the integration of measure, model derived by measures, model derived by nominal value and described geometry, analytical model and BIM tools towards the generation of twin digital model of steel infrastructures [2].

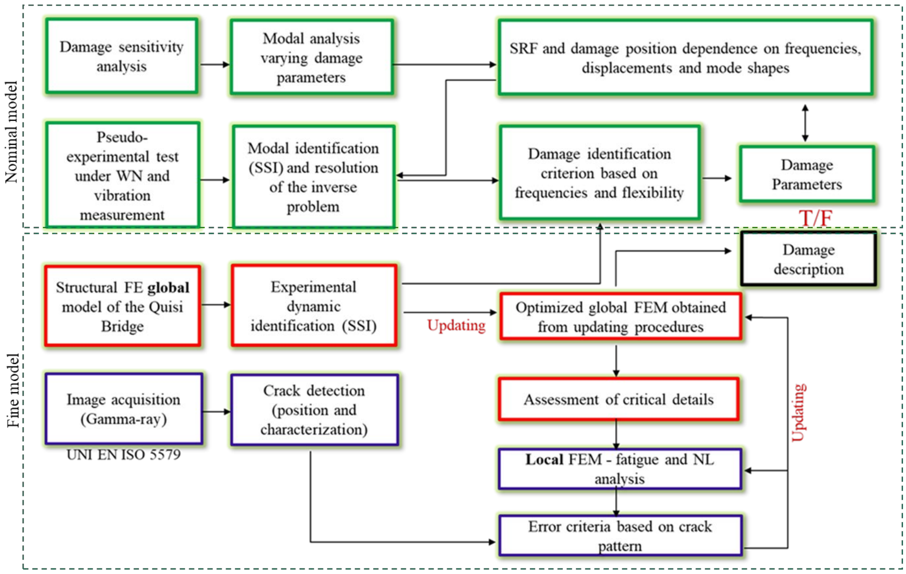

Figure 2. Flowchart of steps i, ii, iii of the proposed procedure

Objective 6: *Models of strands together with the interaction between wires in operational conditions, enhancing the capability to describe their damage and defects through exact observations and measurements.*

Development and lab prototyping of novel solutions for steel strand monitoring

A 3-functionality- into 1-device was planned to be developed for the NDE of seven-wire strand through the use of magnetostrictive effect and elastic guided wave propagation modelling. A rigid tensile bench was designed and manufactured for future experiments. Some simulation results of wave propagation of a seven strand were shown.

Investigation on potential use of the graphene as a corrosion protective coating

The exfoliated graphene nanopletelets provide a good protective coating on Al foils, even if their thickness is not uniform. The electrochemical characterization indicated that the graphene-coated Al substrate offers excellent protection against the corrosive medium. The structural characterization recorded after immersion in 0.5 M NaCl confirmed the presence of a graphene layer even 2 weeks of exposure.

Objective 7: *Marketing strategies for enhancing the benefits of steel structures equipped by sensing and automation for self-inspection and maintenance to enlarge structural life with energy savings and sustainable costs.*

Cost analysis

The analysis of cost was carried out and it showed that the proposed solutions are compatible with the budget generally considered for maintenance as percentage of the total cost of a public construction in Europe. Cost-Benefit Analysis (CBA) was developed for Polvorines but easily extended to any kind of bridge. This analysis compares the conventional solution of inspection/monitoring tasks to Desdemona proposal. Although the first-year cost is higher with Desdemona proposal in the third year our solution decrease the inspection cost with regards to conventional solution.

Involvement of steel industry

Promotion of the involvement of steel industry and its contractors was investigated.

The reports written in this context analyzed how the steel contractor can provide its greatest value to the project and has its greatest opportunity to influence the design adopting measures for enhancing the life-cycle of the steel constructions. The involvement of steel contractor can be used to provide the guidance necessary to ensure the structure delivers and its successive management the highest value for the owner's investment. The needs of steel contractor participation in the early structural design, where its knowledge and experience can be used to its greatest advantage, have been evidenced.

3. Explanation of the work carried per WP

3.1. Work Package 1: Catalogue for sensing and automatic inspection and maintenance of steel structures

The WP1 has been focused on the state-of-art related to inspection, monitoring and maintenance procedures of existing structures belonging to different research area (Figure 3). Main findings of the state-of-art suggest that to maintain performance of constructions within acceptable levels in terms of cost-effective intervention actions through their life cycle it is crucial to implement lifecycle management (LCM) and structural health monitoring (SHM) technology and automation in inspection and maintenance. Concepts of Blind Source separation (BSS), statistical analysis, pattern recognition, machine learning, and principal component analysis have been considered for robust and automated structural health monitoring. Model-based and data-based methods have been discussed evidencing different features of several proposed methodologies for damage detection. Methodologies in damage detection based on data-driven techniques, output-only modal identification has been studied to constitute a basis of the action driven in the activities conducted in the devoted WPs. UAV (drones) and automatic image processing techniques have been evaluated as alternative method for bridge condition assessments. The state-of-art of this technologies with a rapid speed of development has been rapidly grown. Finally, particular attention has been devoted to analyse the state-of-art of new solutions for inspection, such as cable-driven manipulators and mobile robots which constitutes the basis for the developed research.

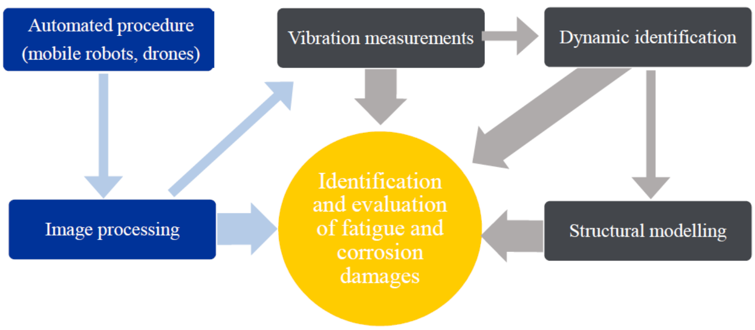

Figure 3. Relationship between research area involved in DESDEMONA project.

3.2. Work package 2: Development and lab prototyping of automatic and robotic solutions for inspection and maintenance

The WP2 has been devoted to the realization of robotic systems for lab testing and monitoring and the realization of novel solutions for strand. Tasks in WP2 have been pursued with strong correlation and communication among partners. Specifically, suitable features and embedding levels of automatic and robotic systems for inspection have been determined for the selected case studies. Five robotic devices for automated inspection of bridges have been detailed. The most important one is a Cable-Driven robot for automated inspection of bridges desk for permanent monitoring purpose. The cable-driven robot for decks inspection has been improved and a novel proposal has been designed, built, and validated (Figure 4). The experimental results demonstrate that the three proposals can be applied for the real cases of study.

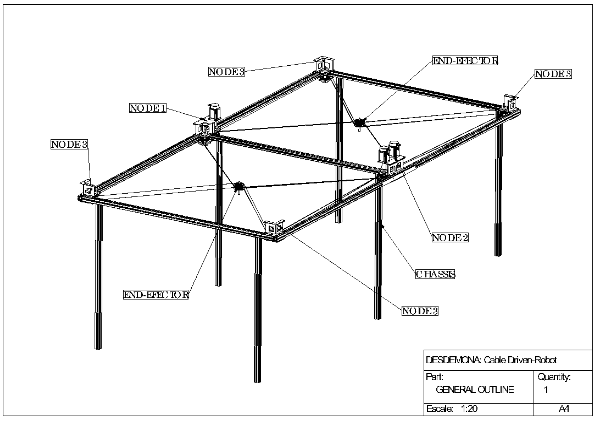

Figure 4. Design of prototype DESDI, a cable-driven robot for automated inspection.

3.3. Work package 3: New design concepts of integrated automatic inspection and maintenance systems for real scale steel structures

The first part of this WP is related to the creation of a database in the DESDEMONA website (https://www.desdemonaproject.eu/activities/) containing three sections: automatic inspection and maintenance systems, steel structure defects and automatic solutions for defect identification. The description of automated systems for inspection has been achieved through the realization of integration of automated cable driven parallel manipulator (CDPM) for bridge inspection in two real case study: the Polvorines Bridge (Figure 5) and the Tabarly Bridge. The CDPM has been designed and it constitutes a potential demonstrator of the integrated system because in can be mounted together with a classical monitoring system on the bridge. Also, the implementation of automated inspection procedures through the use of the robotized systems and the acquirable data are described in the WP3.

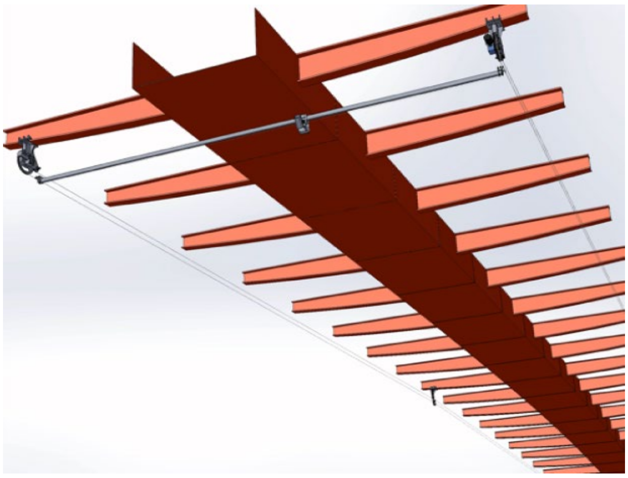

Figure 5. Integration of cable driven parallel manipulator (CDPM) for inspection the Polvorines Bridge.

3.4. Work package 4: Real structure experiments and numerical modeling: towards BIM

This WP is related to the management of data in real scale structures, especially data coming from installed permanent monitoring systems, i.e. accelerometers. Moreover, during the development of the WP in D4.4 the following issues has been taken (as summarized in Figure 6 and Figure 7):

- interoperability between BIM models and finite element based structural analysis software
- automatic model updating from measurements (special attention for cables and cable-supported structure) in order to describe the expected behavior during the life of such structures. BIM have also been used to implement an
- integrated monitoring in which data are stored in the BIM model and processed for a live dynamic update
- adoption of the BIM approach for the purposes of inspection and maintenance automation

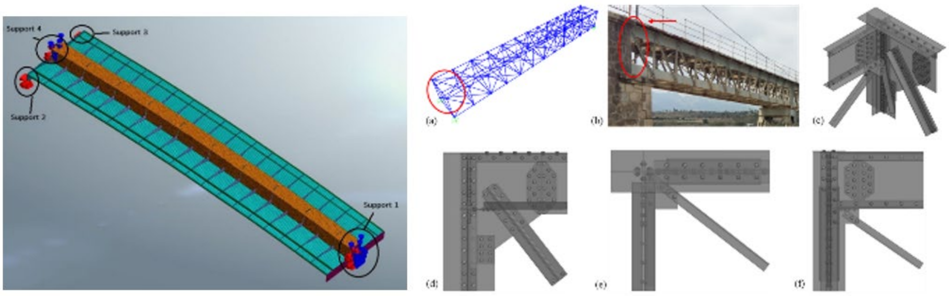

Figure 6. Integrated modelling, digital and structural modelling: Annibaldi and Quisi bridges.

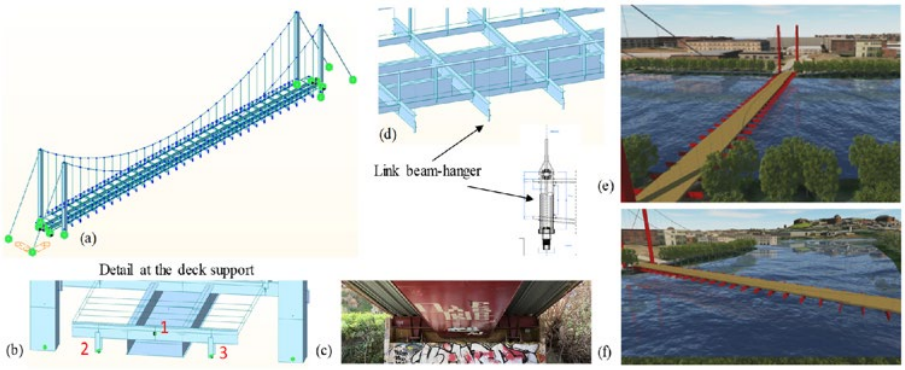

Figure 7. Integrated modelling, digital and structural modelling: Polvorine bridge [8].

In order to proceed towards an interacting model with measurements, once data have been acquired, an efficient global digital data repository involving different complementary experimental observation techniques, standardized procedures and enabling the analysis of accuracy, spatial resolution, correlation and complementarity of the experimental information collected, it is also developed. Finally, for the Tabarly Bridge, the data treatment has been reached using data driven techniques to predict the behavior of structures through the use of machine learning algorithms (Artificial Neural Network ANN). This WP also focuses on the interoperability between BIM models and finite element models. BIM have also been used to implement an integrated monitoring in which data are stored in the BIM model and processed for a live dynamic update adoption of the BIM approach for the purposes of inspection and maintenance automation. An application of processed monitoring data integrated in BIM environment applied on the Tabarly Bridge, it is described Figure 8.

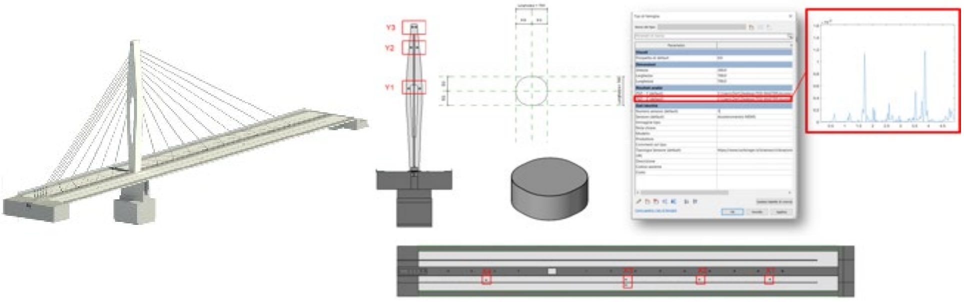

Figure 8. Monitoring data integrated in BIM environment applied on the Tabarly Bridge.

3.5. Work package 5: Data fusion techniques for damage detection through integration of different sources of measurements

WP5 focused on the long-term tracking of modal parameters of monitored structures, summarizing advanced input-output and output-only methodologies to mitigate the influence of environmental and operational factors on modal parameters estimates and describing the construction of robust software for vibration-based damage detection. A software package that integrates most of the presented algorithms was developed for the management and processing of the large amounts of data collected by permanent dynamic monitoring systems. The developed monitoring software was named *DynaMo* (Figure 9), which stands for DYNAmic MOnitoring. Its main goal is to transform the collected acceleration time series into meaningful information from the structural behaviour point of view.

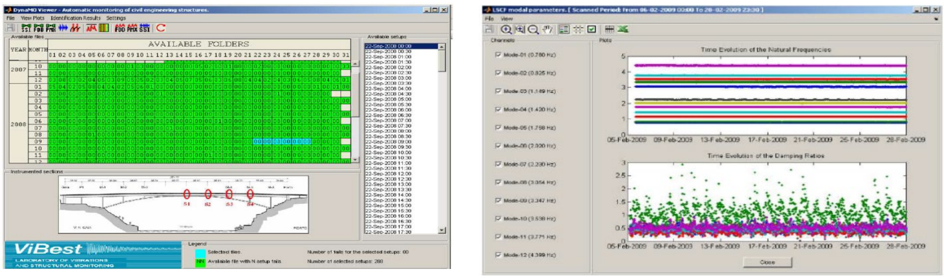

Figure 9. Main window and plots produced by the developed DynaMo Viewer software.

The most important contribution of the research was the definition of monitoring frameworks for damage detection, its implementation and the validation with monitoring data collected during more than one year. The tools used for the minimization of operational and environmental effects on modal properties were described with reference to two case studies, a cable-stayed bridge and an onshore wind turbine. The latter is showed in Figure 10.

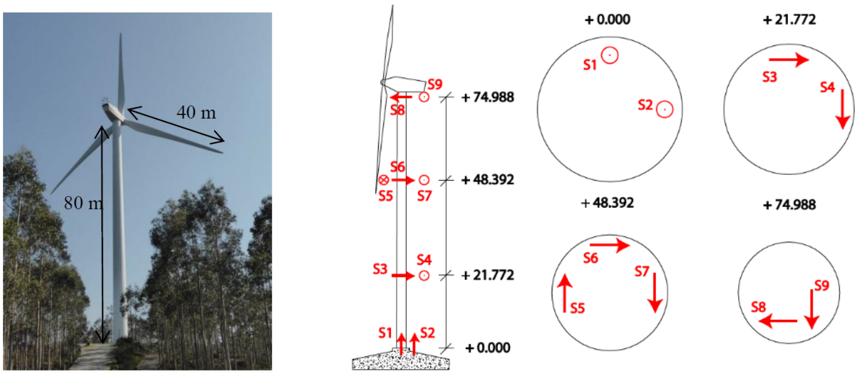

Figure 10. Monitored wind turbine and measuring setup.

Finally, structural health monitoring and damage detection were carried out by using machine vision-based sensing technology. Two laboratory experiments showed the potentiality of the vision displacement sensor. A procedure based on the processing of pixel intensity was proposed to conduct SHM by the direct processing of pixel intensity time variations. In the context of image-based SHM, a third research activity was carried out on a real case study, a cable-stayed pedestrian bridge, to extract cables vibrations from high-speed camera images and to estimate their axial forces.

3.6. Work package 6: Strategies for favoring the penetration in to the market of steel structures equipped by sensing and automation for self-inspection and maintenance

In this WP the cost was evaluated for the following solution: cable driven robot, wheeled robot and hybrid robot. Installation and management procedures of automated proposed robotic solutions for periodic inspection and permanent monitoring were detailed. Both I&M for Permanent Monitoring systems and Periodic Inspection systems was analyzed in term of installation and maintenance costs. The analysis of cost confirms that the proposed solutions are compatible with the budget generally considered for maintenance as percentage of the total cost of a public construction in Europe. Cost-Benefit Analysis (CBA) was developed for Polvorines case of study but easily extended to any kind of bridge. This analysis compares the conventional solution of inspection/monitoring tasks to Desdemona proposal. Although the first-year cost is higher with Desdemona proposal in the third year our solution decrease the inspection cost with regards to conventional solution. For a ten-year time-windows, Desdemona reduce the inspection/monitoring cost about a 40% (Figure 11).

Furthermore, a list of possible stakeholders was defined and a way to promote the involvement of structural steel industry and its contractors was investigated. The involvement of steel contractor can be used to provide the guidance necessary to ensure the structure delivers and its successive management the highest value for the owner's investment.

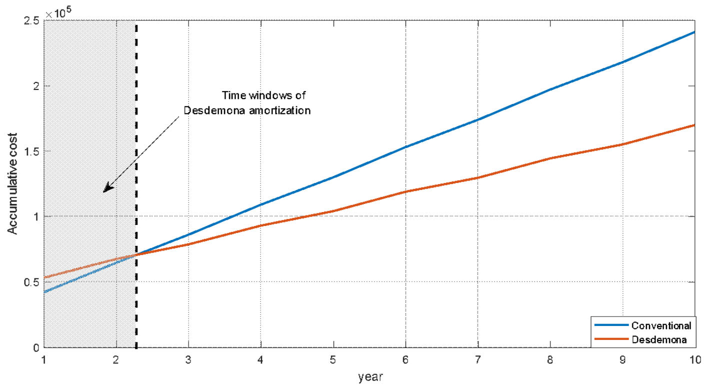

Figure 11. Cost analysis: accumulative costs.

3.7. Work package 7: Coordination of the project

This WP consisted of the activities related to dissemination developed within the coordination of the project. The achieved results of the research activity have been disseminated at National and International scientific levels. The following goals have been achieved:

1. a few days before the Kick Off Meeting – DESDEMONA KOM on 1st June 2018 a press release has been launched through the devoted Sapienza Office
2. organization of dissemination actions of the Project's scientific activities, Special Issues in relevant Journals, public events, workshops and the APESS 2019 – Asia-Pacific-Euro Summer School on Smart Structures Technology and held in Rome chaired by the PI;

3. presentation and communications in conferences and publications in international journals;
4. activation of a website within the end of the first semester of the project;
5. preparation of an Extended Summary, with illustration of the achieved results.

The achievement of Project's objectives can be ascertained from an examination of the scientific production which includes also scientific papers published in well-referenced journals and in open access. Additional verification elements of the achievement of the project's goals with respect to dissemination can be considered as: (a) the reports of internal work meetings of consortium members, aimed at discussing the state of research; (b) public events organized in Rome.

Guidelines for standardization of the proposed methodology have been defined and reported on website in "Activities" page (https://www.desdemonaproject.eu/activities/). A database of automatic solutions for inspection has been created and three sections have been implemented:

1. Automatic inspection and maintenance systems: the features of the proposed automatic and robotized solutions for inspections of steel structures are reported;
2. Steel structure defects: the features of the main defects observed in steel structures are described;
3. Automatic solutions for defect identification: the more suitable automatic solutions for each defect type are delineated.

The organization of these guidelines on website is extensively described in the "Database for automatic inspection and monitoring of steel structures".

The publications produced within the project are part open access and part are accessible via a repository for scientific publications such as www.zenodo.org [1-35].

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