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New software for dynamic identification and optimal sensor placement of civil structures and infrastructures

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ABSTRACT

The dynamic identification of structures, such as buildings and bridges, is fundamental for the assessment of structural performance, safety and maintainability, as it involves the identification of modal parameters that define the dynamic behaviour of a structure. Operational Modal Analysis (OMA) has emerged as the preferred method for this purpose, exploiting environmental vibrations without requiring external excitation. Although commercial software packages for OMA exist, they often limit user control over key settings, leading some researchers to develop customised tools to improve OMA methodologies and explore innovative identification techniques. However, the availability of stand-alone software with the versatility and advanced capabilities required to meet the different needs of practitioners and researchers is still limited. This paper presents DYMOS, a new OMA software designed to be used with environmental vibration data. DYMOS incorporates state-of-the-art algorithms for vibration-based modal identification and Optimal Sensor Placement (OSP), offering extensive customisation possibilities for practical and research applications. The second task of the software, dedicated to the OSP, allows for the execution of OSP analyses adopting as input either experimental or numerical data, the latter with the possibility to be automatically imported from a finite element software. This study describes the functionality of DYMOS and demonstrates its effectiveness in civil engineering through applications to two real-world case studies: a building with complex geometry and a newly built cable-stayed bridge.

Keywords: OMA software, ambient vibration tests, optimal sensor placement, civil engineering structures, acceleration recordings

1. INTRODUCTION

The dynamic identification of civil engineering structures is crucial for assessing structural health, understanding their dynamic behaviour, and guiding maintenance strategies [1,2]. This process involves Operational Modal Analysis (OMA) to identify modal parameters from ambient vibrations and Optimal Sensor Placement (OSP) to optimize sensor positioning for accurate data collection [3]. Both tasks require specialized tools capable of handling complex data processing, analysis, and visualization. DYMOS is a newly developed software within the MATLAB environment that aims to streamline and enhance the dynamic identification workflow by integrating advanced methodologies for both OMA and OSP.

This paper presents the architecture, features, and applications of DYMOS, highlighting its innovative tool for mode shape plotting. Through two real case studies, this work demonstrates how DYMOS provides an effective and user-friendly solution for dynamic structural identification and OSP.

2. BRIEF DESCRIPTION OF DYMOS ARCHITECTURE AND ALGORITHMS

DYMOS is a MATLAB-based software designed for the comprehensive dynamic characterization of structures. It consists of two main components (**Figure 1)**: the first focuses on OMA, while the second handles OSP.

The OMA module provides tools for data pre-processing, modal identification, mode selection, data merging from multi datasets, and graphical result representation. It features advanced pre-processing techniques, including noise reduction, Butterworth filtering, down-sampling, linear detrending, and manual signal cutting. DYMOS supports time domain (Stochastic Subspace Identification, SSI-COV and SSI-DATA) [4,5,6] and frequency domain (Enhanced Frequency Domain Decomposition, EEFDD) [7,8] identification methods, offering manual and automatic mode selection using clustering algorithms [9]. It also facilitates dynamic identification with non-simultaneous measurements through the Post Separate Estimation Re-scaling (PoSER) technique [10]. The OSP module supports analyses based on numerical or experimental data and integrates CSI SAP2000 via a SAP-MATLAB toolbox [11]. It offers five OSP methods: Effective Independence (EI), Information Entropy (IE), Eigenvalue Vector Product (EVP), Mode Shape Summation Plot (MSSP), and Average Driving Point Residue (ADPR) [12]. This module also allows the calculation of two common metrics to comprehensively compare all the OSP method results: the Average Value of the off-diagonal terms of the AutoMAC Matrix (AVAM) and the Information Entropy Index (IEI) [13]. Key strengths of DYMOS include its separate mode selection module, customizable input parameters, and innovative CAD-based graphical representation, enhancing ease of use while reducing computational effort. The dedicated OSP module is particularly useful for planning dynamic tests and designing SHM systems, distinguishing DYMOS from other dynamic identification tools.

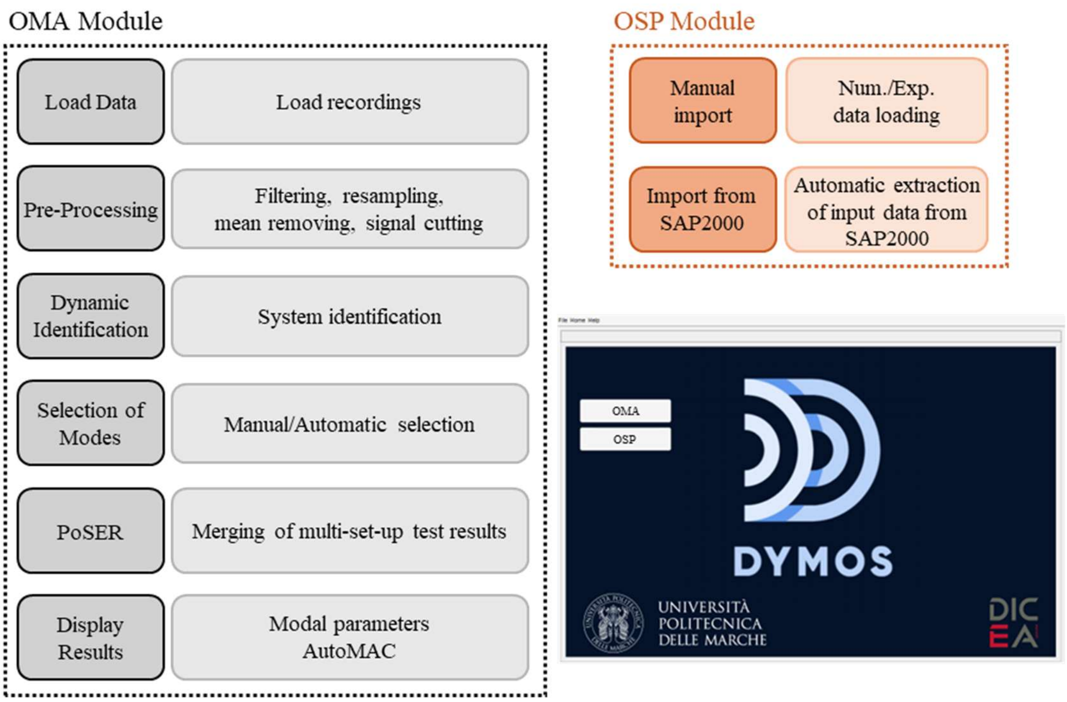

Figure 1. DYMOS architecture and description of modules.

3. APPLICATION TO REAL CASE STUDIES

This paper shows the effectiveness of DYMOS in dynamic identification and OSP for two civil engineering structures tested using Ambient Vibration Tests (AVTs). These structures feature complex geometries and articulated designs, exhibiting dynamic behaviours that require a precise and challenging modal identification process. For the sake of brevity, only the software screens related to the building analysis are presented, while results are proposed for both.

3.1. Description of case studies

The first case study is a new cable-stayed bridge built in Central Italy (**Figure 2a**). The bridge spans approximately 190 m and features a continuous steel-concrete composite deck with two traffic lanes. The deck width varies from 19.2 to 22.8 m and is supported by 40 diagonal stays. On its downstream side, the bridge includes a curved section designed for pedestrian and cycling paths. The second case study focuses on a multi-block residential building located in Central Italy as well (**Figure 2b**). This structure consists of four Reinforced Concrete (RC) frame blocks with masonry infills, separated by structural joints. The building has an "L- shaped" layout, with a maximum length of 44 meters and a shorter span of 28 m. Each block is approximately 11 m wide and comprises six stories, reaching a total height of 18.5 m.

To investigate their dynamic behaviour, both structures were tested using AVTs. The instrumentation included uniaxial piezoelectric accelerometers with a sensitivity of 10,000 mV/g and a measurement range of ±0.5 g. These sensors were connected via coaxial cables to NI-9230 3-channel acquisition modules, housed in 4-slot NI cDAQ-9185 and 8-slot NI cRIO-9045 chassis. The modules were networked using ethernet cables, with data acquisition managed through custom LabVIEW software.

3.2. Signal pre-processing

The "Load Data" module in DYMOS allows users to import dynamic test signals, assess quality, and detect anomalies using spectrum visualization (**Figure 3a**). It automatically identifies measurement channels and enables users to assign custom names. After specifying the sampling frequency, users can generate Power Spectral Density (PSD) plots up to the Nyquist frequency and compare different channels. The "Pre-Processing" module (**Figure 3b**) supports flexible pre-processing procedures, including data resampling (e.g., from 1024 Hz to 102.4 Hz for both case studies) and linear detrending. Users can configure parameters for Welch's PSD estimation, with a 20-second window and a 10-second overlap recommended for optimal results.

3.3. System identification

The "Dynamic Identification" module (**Figure 4a**) enables system dynamic identification and result visualization. It can be used either immediately after preprocessing or with pre-processed recordings loaded from an external file. In both cases, the sampling frequency (original or resampled) must be specified. Users can choose from three identification methods, namely SSI-COV, SSI-DATA, and EFDD. When a method is selected, the corresponding input parameters must be provided. The module also allows users to select specific measurement channels for the identification process, offering flexibility to use either the full dataset or a reduced set of channels.

Figure 2. Case studies: (a) cable stayed bridge, (b) residential building.

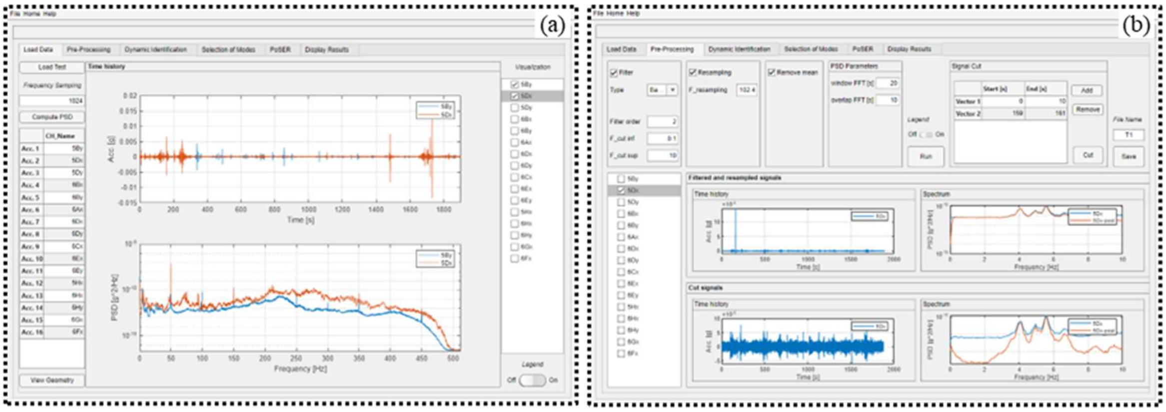

Figure 3.DYMOS: (a) "Load Data" module, (b) “Pre-Processing” module.

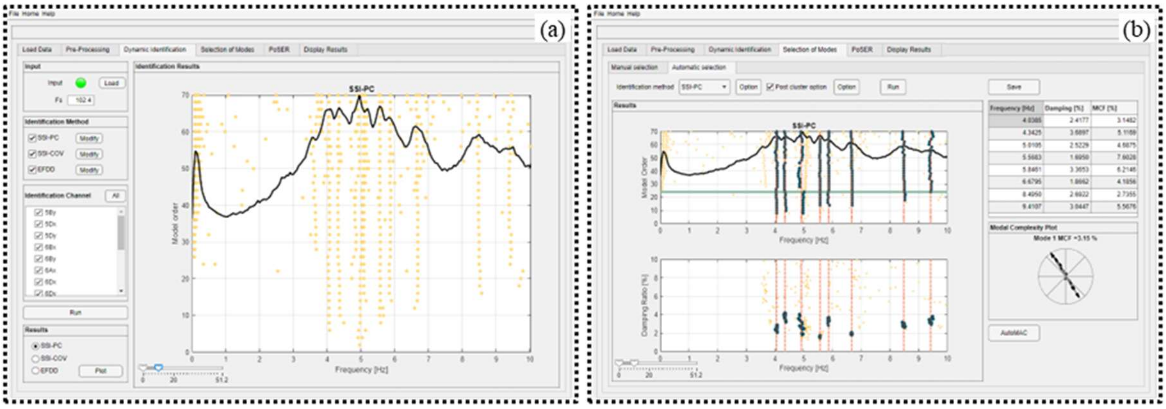

Figure 4. DYMOS: (a) “Dynamic Identification” module, (b) “Selection of Modes” module.

Once identification is complete, results for each method are displayed. For time-domain methods, a stabilization diagram shows all identified solutions overlaid on the first Singular Value (SV) of the signal spectra. The diagram starts with a minimum model order of 2 and increases in increments of 2 up to the user-defined maximum. For EFDD method, only the first SV is displayed at this stage.

The “Selection of Modes” module (**Figure 4b)** offers two methods for selecting identified modes: manual and automatic. Manual selection, while guided, requires in-depth user expertise. The automatic method employs a clustering algorithm to select stable modes based on a few input parameters. While simpler, this method still requires basic knowledge to avoid unrealistic inputs and unreliable results. After mode selection, DYMOS displays the modal parameters for each chosen mode, including frequency, damping ratio, and Modal Complexity Factor (MCF). A table lists these values, alongside a modal complexity plot different for each selected mode. The AutoMAC matrix is also provided to assess the correlation between selected solutions. Users can export the results as a .xlsx file containing frequency, damping ratio, MCF, and normalized modal displacement for each mode.

3.4. Merging of multi-set-up test results

AVTs on civil engineering structures typically require measuring responses at many locations to achieve sufficient spatial resolution for accurately capturing all modes. However, limited sensor or acquisition channel availability often necessitates multiple test setups. This involves keeping some sensors fixed as reference points while moving others to cover the entire structure. In such cases, dynamic identification relies on combining data from several non-simultaneous measurement configurations. This is achieved by using reference sensors and applying merging techniques. Due to the size and complexity of both structures, multiple sensor configurations and non-simultaneous AVTs were conducted for dynamic testing. DYMOS supports this process through the PoSER technique (**Figure 5a**).

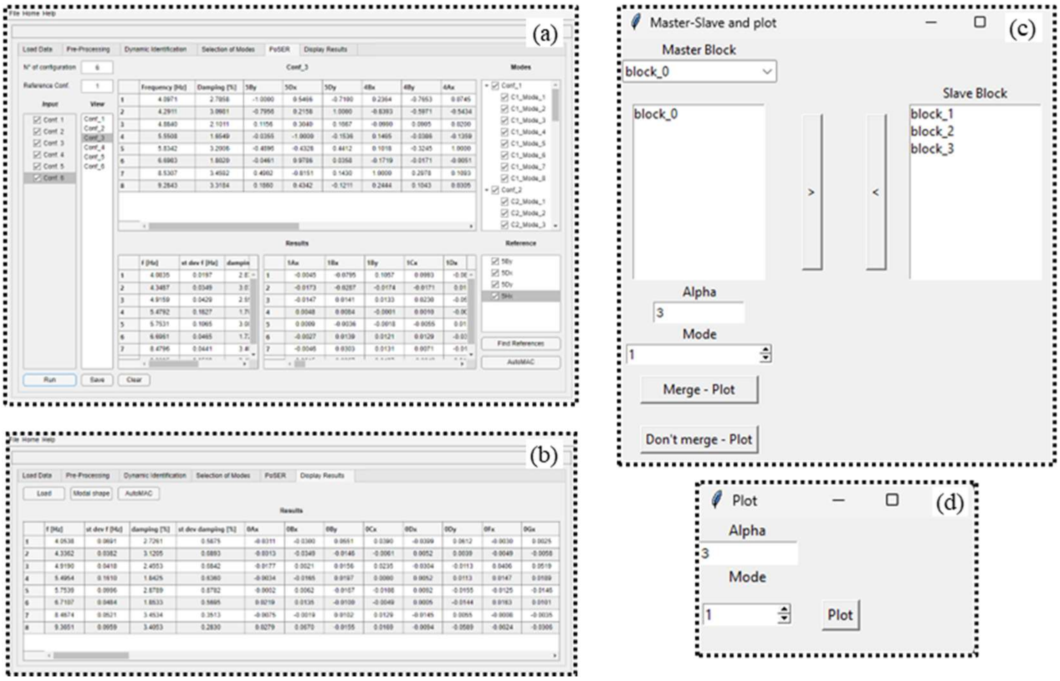

Figure 5. DYMOS: (a) "PoSER" module, (b) "Display results" module, (c) tool for plot mode shapes of buildings, (d) tool for plot mode shapes of bridges.

3.5. Display results

The "Display Results" module (**Figure 5b**) enables the visualization of modal shapes by allowing users to import geometric models from CAD drawings in .dxf format. This approach makes building the geometric model and measurement grid faster, simpler, and more intuitive. To begin, users load the modal parameters saved during mode selection for a single test configuration or after applying the PoSER technique. The module displays a table summarizing the identified modal parameters. Next, DYMOS requires the geometric model of the structure. Then, an interactive window enables users to select the mode to display and adjust the mode shape scaling factor. DYMOS includes specialized tools for plotting the deformed shapes of bridges and buildings with various geometries (respectively **Figure 5d** and **Figure 5c**).

For bridges, the deck must be divided into 4-edge surfaces (**Figure 6a**), continuous (with a common edge) for bridges with continuous decks or separated for simply supported span decks. The software deforms each surface based on the 3D displacements of the four vertices (**Figure 6b**). Additional bridge components, such as piers, stays, and pylons, can be drawn using undeformed line elements, which form the background to the deformed deck mode shapes. Each deck surface should include four tri-axial measurement points, two horizontal and orthogonal in the plane, and one vertical, representing the measurement axes with labelled lines. For the buildings, the representation of the modal shapes of each floor (**Figure 7b**) is based on the rigid plane assumption, i.e., the kinematics of the floor is described by 3 DOFs (2 translations and 1 rotation in the plane) (**Figure 7a**). DYMOS enables visualization of building mode shapes using the provided modal displacements. It displays both the deformed and undeformed shapes (the latter in light grey) to aid interpretation. The display tool offers two visualization options: separated and merged plot (**Figure 7c**). The separated plot, in which each building block is shown independently, is useful for representing mode shapes of adjacent structures separated by structural joints. Instead, in merged plot, the edges of separate blocks are joined to create a unified modal shape, suitable for buildings with complex layouts but a single structural body. To use this option, a master block must be defined, to which the deformations of slave blocks will connect. This flexibility enhances clarity when interpreting complex structural behaviours. For bridges and buildings, the labels of the measurement axes must correspond to those assigned in the "Load Data" module.

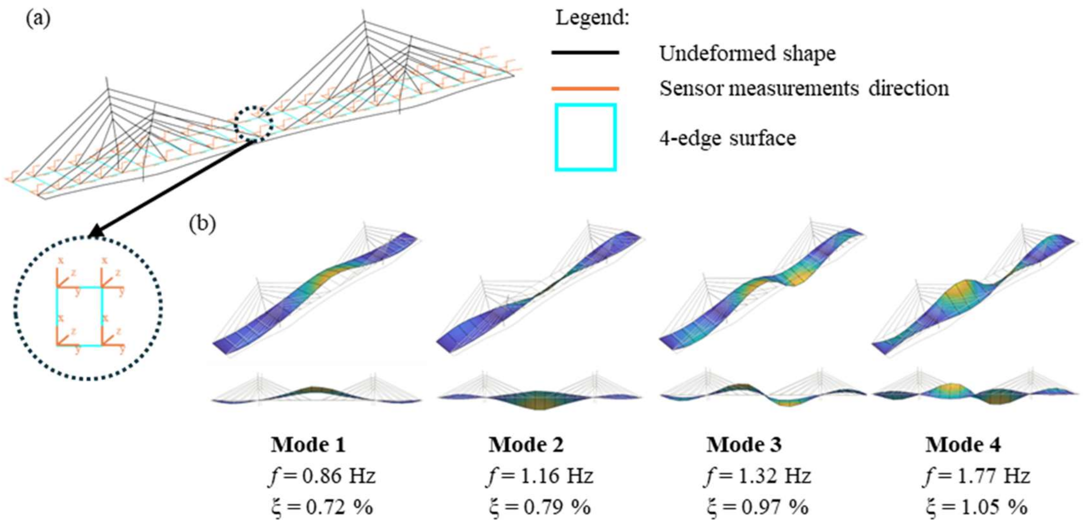

Figure 6. Bridge results and display: (a) CAD model, (b) identified modes.

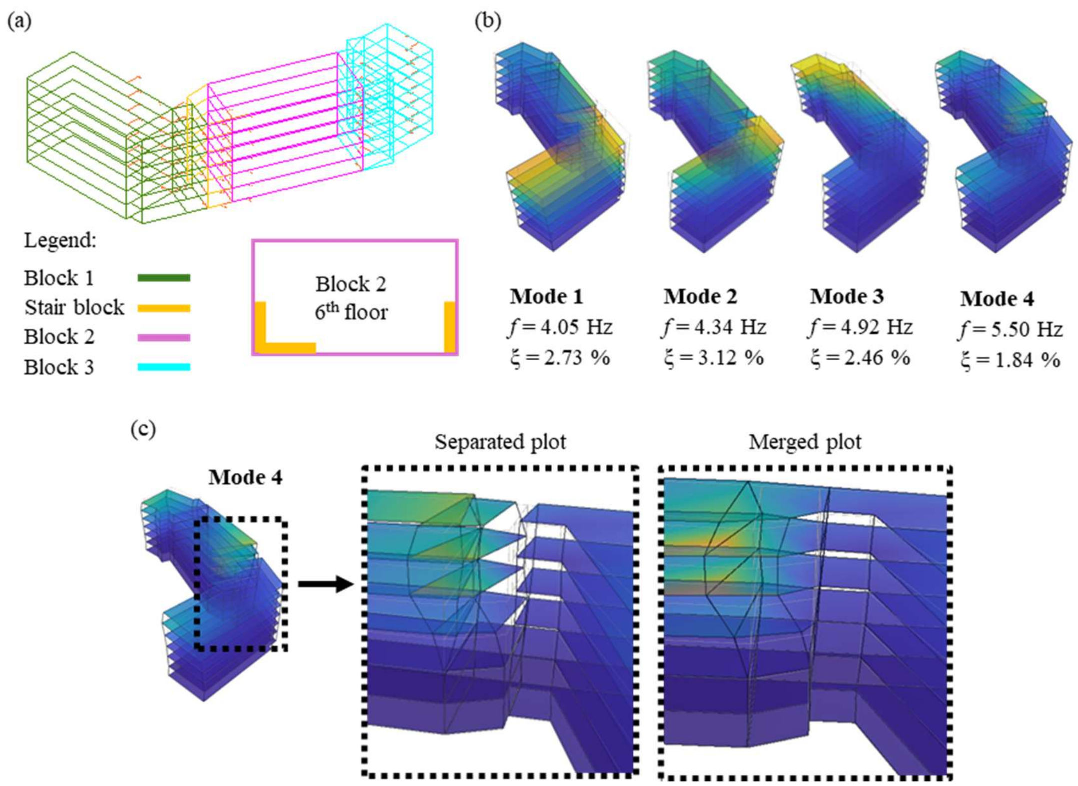

Figure 7. Building results and display: (a) CAD model, (b) identified modes, (c) separated plot or merged plot view of mode shapes

3.6. Optimal Sensor Placement

DYMOS module for OSP (**Figure 8**) helps identify the optimal sensor configurations for dynamically testing and monitoring the two case studies. In this work, experimental results are used as a basis for the OSP analysis. The OSP starts by providing the identified modal displacements after applying PoSER to the DOFs tested during the AVTs. A total of 84 DOFs for the building and 60 for the bridge are considered. Before conducting the analysis, users define a few key inputs: the number of modes to identify (4 for the bridge, 8 for the building), the minimum number of sensors to be employed (7 for the bridge, 8 for the building), and the maximum number of sensors that could be used (in this case 20 sensors for both were assumed). The maximum number of sensors helps build metric graphs to assess OSP method performance as the number of sensors increases, while the minimum ensures enough sensors to avoid spatial aliasing and clearly identify the mode shapes. For the bridge, a higher number of sensors (7 DOFs instead of 4) is used to validate the current sensor configuration of monitoring system installed on the bridge. The EI and IE methods are considered the most effective, as they better identify higher modes for both structures. For the bridge, EI and IE select joints along the deck; for the building, all methods select joints at higher levels, where larger modal displacements occur. This is confirmed by the metric graph (**Figure 9b** and **Figure 9d**), which shows no significant variation in AVAM and IEI for EI and IE as the number of DOFs increases. For the building, metrics improve with an increasing number of sensors, such as up to 14 sensors. In **Figure 9a** and **Figure 9c** the results of the EI method analysis are shown for the bridge and for the building.

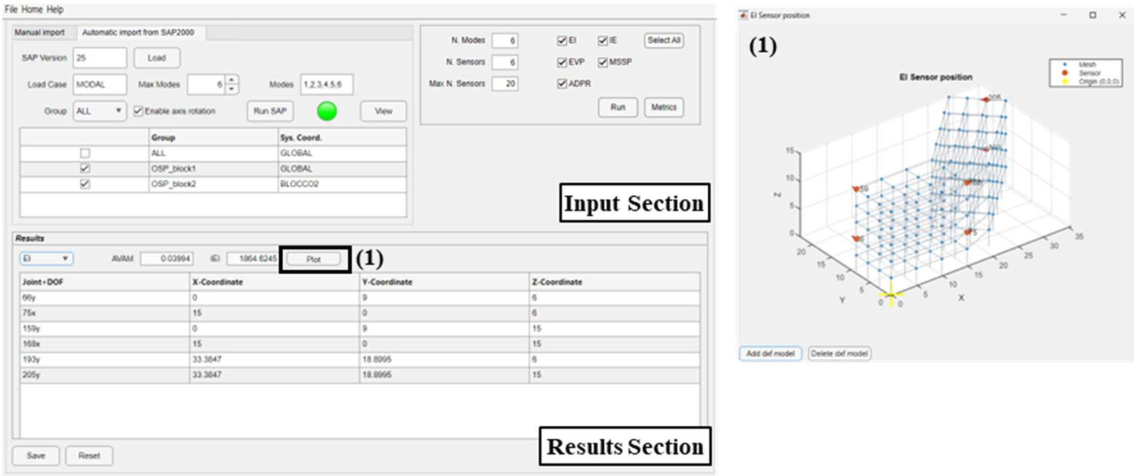

Figure 8. DYMOS: OSP module, input and results sections.

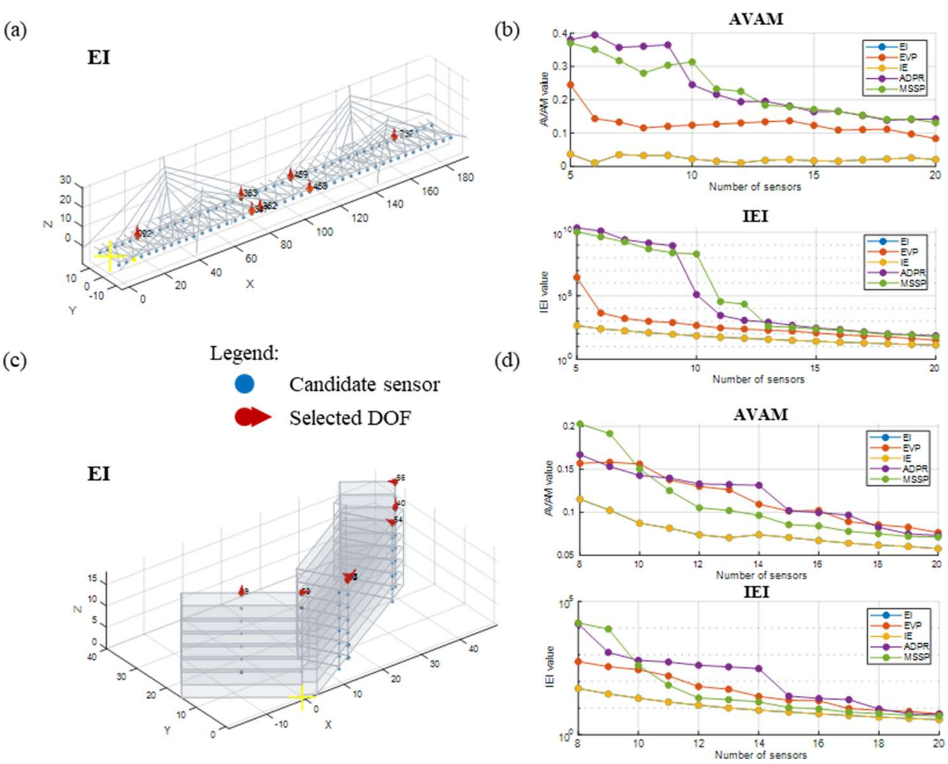

Figure 9. OSP results: (a) EI method for bridge, (b) metric plots for bridge, (c) EI method for building, (d) metric plots for building.

4. CONCLUSIONS

DYMOS is a powerful new software for the dynamic identification of structures using ambient vibration tests data. It integrates advanced algorithms for vibration-based modal identification and optimal sensor placement, offering customizable modules that meet both professional and research needs. Through detailed analysis of two real case studies, a cable-stayed bridge and a complex building, this paper demonstrated DYMOS's effectiveness in performing operational modal analysis, mode selection, and optimal sensor placement. Additionally, DYMOS provides intuitive visualization tools that simplify the creation of geometric models using CAD drawings for display the mode shapes and the results of optimal sensor placement analysis. Overall, DYMOS presents a significant advancement in the dynamic identification field, providing a versatile and user-friendly solution for civil engineering applications.

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