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# Multivariate analysis of multi-sensor data for assessment of timber structures: Principles and applications

Jakub Sandak *, Anna Sandak, Mariapaola Riggio

*CNR-IVALSA, Via Biasi 75, 38010 San Michele all'Adige (TN), Italy*

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ABSTRACT

The proper timber structure assessment is of great importance to assure safe service of buildings as well as to preserve cultural heritage objects for future generations. However, due to peculiar anatomic structure of wood, anisotropy and heterogeneity, its characterization is a problematic task. Several methods are used nowadays for improving existing structure assessment routines, including also continuous monitoring of the structure performance. Current trend for using multiple sensors simultaneously is more favorable than a single sensor approach due to superior representation of the real-world cases. Moreover, the availability of novel statistical tools to handle many variables concurrently is another motivation for rapid changes within the field of measurement technology. It is important, therefore, to assure proper pre-processing of the signals from sensors, appropriate data fusion and optimal data analysis. The integrated use of non-destructive testing methodologies and data handling techniques to assess, monitor and predict properties of wood within structures and buildings is briefly described in this work. Examples for successful applications of the different data analysis techniques on the assessment and monitoring of civil engineering constitutions are reported.

Multi-sensor approach may be a very attractive alternative to the conventional assessment and can provide supplementary data to be considered when inspector decision is made. It is assumed that, after additional developments, such methodologies can serve as assisting tools for non-destructive assessment of the wooden structures, service life prediction of structural elements and to support selection of optimal conservation process.



## 1. Introduction

Currently booming engineering research provides us with numerous methods to be used for improving (reengineering) existing structure assessment routines, including also continuous monitoring of the structure performance. The availability of novel statistical tools to handle many variables simultaneously is another stimulus for rapid changes within the field of measurement technology and the sensors domain. Current trend for using multiple sensors simultaneously is more favorable than a single sensor approach due to far better representation of the real-world cases: the world is multivariate. The integrated use of non-destructive testing (NDT) methodologies and data handling techniques to assess, monitor and predict properties of wood within structures and buildings is briefly described in this work. It is not intended here to provide a complete description of the available sensors, algorithms or data mining methods, but rather to state all the important issues related, as well as to highlight the potential applications for assessing or monitoring of timber structures. Some examples for successful applications of the different data analysis techniques are reported, focusing not only on the timber structures, but also on the assessment and monitoring of civil engineering constitutions in general.

Multi-sensor monitoring generates new issues and challenges, where the fusion of different sources of information is fundamental. Data collected from different types of sensors are often based on diverse physical phenomena, therefore interpretations of results is complicated. Some of sensors may be more accurate than others, since these are more sensitive in certain condition. Finally, the data collected are usually correlated with each other, what makes it necessary to interpret these together [1].

A general flowchart of the multi-sensor approach in timber structures assessment is summarized in Fig. 1. It consists of several layers, including sample/object/case, sensors measuring member

* Corresponding author.
*E-mail addresses:* sandak@ivalsa.cnr.it (J. Sandak), anna.sandak@ivalsa.cnr.it (A. Sandak), riggio@ivalsa.cnr.it (M. Riggio).

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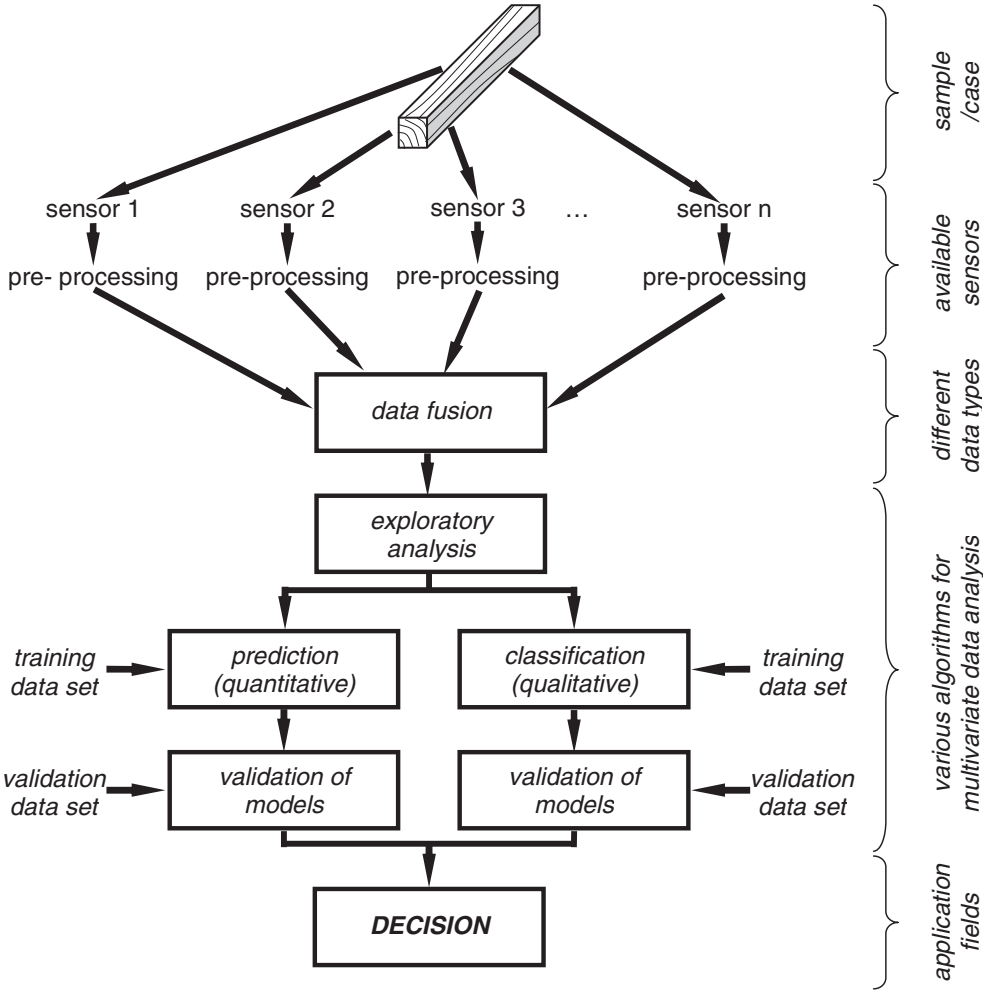


**Fig. 1.** Multi sensor approach combined with multivariate analysis for assessment of timber structures.

properties (through generating various types of data), and numerical models/tools to deal with such data in order to support expert in decision making. Some more detailed discussion on each layer is presented below.

## 2. Sample

Samples, cases or objects are the physical units on which the evaluation or measurements are performed. It can be a single wooden member or the whole structure, depending on the scope of evaluation and/or the goal of inspection. There are numerous sample(s) characteristics of interest, including:

- *Material properties:* density, modulus of elasticity, strength, etc.
- *Degradation stage of wooden members due to biotic agents:* rot decay, damage by insects, bacteria, etc.
- *Degradation stage of wooden members due to a-biotic agents:* waterlogging, weathering, aging, chemical degradation, etc.
- *Presence, position and incidence of strength-affecting defects in wooden members:* knots, checks, slope of grain, etc.
- Presence of damp areas and not uniform moisture distribution in wooden members.
- *Mechanical damage in wooden members and connections:* cracks, delaminations, etc.
- *Geometrical alterations in the wooden members and assemblies:* distortions, deformations, etc.
- *Overall performance of the structure:* load capacity, risk of failure, etc.

Material variability and interaction with the environment are the two major obstacles in quantifying the above mentioned characteristics. Understanding sources of variability is important because they will affect the experimental design of the investigation. Generally, two sources of variability can be defined that are applicable in timber structures: variability "within" (a single timber member, a timber assembly, etc.) and variability "between" (different sections in a beam, different timber members, etc.) [2]. It is fundamental to properly address the issue of variability, for the selection of the more appropriate sampling strategy. Recommendations regarding representative sampling for reliable data analysis were published by Petersen et al. [3]. They have used Theory of Sampling approach for presenting correct sampling principles, explain common sampling errors and present various sampling strategies.

## 3. Sensors

It needs to be emphasized at this point that the basic (and unavoidable) method for assessing timber structures on site is visual inspection [4]. However, it can be complemented by a series of instrumental techniques, giving information on unreachable objects, about not-visible features, and on measurable/quantifiable parameters.

The range of sensing techniques suitable for characterization of wood within structures is very wide. Moreover, continuous development of sensors provides new solutions, concepts and

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