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Deformation and structural health monitoring of infrastructure projects: Geodetic methods, new technologies and management aspects

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Abstract

The present thesis focuses on instrumented monitoring systems, emphasizing geodetic monitoring methods, emerging technologies and managerial aspects of such systems. The aim of the study is (i) to examine existing principles, methods and frameworks of structural monitoring, (ii) to investigate the integration of new technologies into the monitoring process, (iii) to assess the current situation in Greece and (iv) to accentuate the role of monitoring as a project management tool, contributing to more rational and objective, data-driven decisions.

A comprehensive literature review was conducted, with Scopus and Google Scholar being principal sources. To explore the potential of emerging technologies, publications from the 5th Joint International Symposium on Deformation Monitoring were analyzed. Moreover, to demonstrate the managerial role of monitoring as decision making tool, research papers from focus group “Data-informed Decisions for Structures and Infrastructures” were examined.

The analysis led to the following key findings: the main factors limiting widespread adoption of monitoring systems in practice are their cost and the reluctance of project owners to invest in them. A solution to this issue can be found through the Value of Information (VoI) framework, which quantifies and translates the benefits of monitoring into monetary terms, thereby providing a rational basis for investment decisions. Beyond economic barriers, technical and computational challenges were also identified. These can be addressed through emerging technologies, which enable monitoring in inaccessible or hazardous areas, automated result generation using advanced algorithms, more efficient data management, and improved communication among stakeholders.

In the case of Greece, no binding or standardized framework was identified. Monitoring practices among large-scale infrastructure projects appear heterogeneous, which is partially justified by the diversity of structural types and conditions. Nevertheless, the case studies confirmed the theoretical advantages of monitoring, demonstrating its value in identifying deviations from design assumptions, correlating deformations with probable causes, providing timely information during emergencies, and informing maintenance and rehabilitation actions.

Finally, the future of monitoring is population-based monitoring systems, which exploit the capabilities of machine learning and require fewer training data. However, the implementation of such systems requires both the integration of advanced technologies into the monitoring process and the establishment of clear, detailed standards to ensure the quality and reliability of the collected data.

In conclusion, this study presents instrumented structural monitoring not merely as a technological tool but as a holistic methodology that integrates measurement, data analysis, and management. By doing so, it underscores monitoring as an essential instrument for more efficient, informed, and sustainable infrastructure management.

Περίληψη

Η Ευρωπαϊκή Ένωση καλείται να διαχειριστεί ένα γερασμένο απόθεμα υποδομών μέσω πεπερασμένων διαθέσιμων πόρων. Η αναμενομένη υποβάθμιση των κατασκευών λόγω ηλικίας, κόπωσης και φθοράς των υλικών εντείνεται από ακραία καιρικά φαινόμενα, όπως αυτά της κλιματικής αλλαγής, και έκτακτα γεγονότα. Η Ελλάδα καλείται να αντιμετωπίσει τις παραπάνω προκλήσεις, ενώ η θέση της σε μία ευρύτερη σεισμικά ενεργή περιοχή, αποτελεί μία επιπλέον πρόκληση. Είναι σαφές ότι η χρήση συστημάτων που προσφέρουν πολύτιμες πληροφορίες σχετικά με την πραγματική κατάσταση των κατασκευών κρίνεται πιο επιτακτική από ποτέ, ώστε να μην τεθεί σε κίνδυνο η ασφάλεια και επιτελεστικότητα των κατασκευών.

Η παρούσα διπλωματική εργασία πραγματεύεται τα ενόργανα συστήματα παρακολούθησης, δίνοντας έμφαση στα γεωδαιτικά δίκτυα, τις νέες τεχνολογίες και τη διαχειριστική πτυχή των συστημάτων αυτών.

Σκοπός της εργασίας είναι η μελέτη των υπαρχουσών αρχών, μεθόδων και πλαισίων ενόργανης παρακολούθησης, η εξέταση της ενσωμάτωσης νέων τεχνολογιών στη διαδικασία της παρακολούθησης, η μελέτη της υφιστάμενης κατάστασης στην Ελλάδα και η ανάδειξη των συστημάτων αυτών ως εργαλεία διαχείρισης έργων, καθώς οδηγούν σε πιο ορθολογικές/ αντικειμενικές αποφάσεις που βασίζονται σε δεδομένα.

Στο πλαίσιο αυτό, πραγματοποιήθηκε βιβλιογραφική αναζήτηση. Κύριες πηγές, των αναφορών που μελετήθηκαν, αποτέλεσαν οι διαδικτυακοί τόποι Scopus και Google Scholar. Για τη διερεύνηση των δυνατοτήτων των νέων τεχνολογιών μελετήθηκαν δημοσιεύσεις του 5ου Συνεδρίου Παρακολούθησης Παραμορφώσεων (JISDM) που έλαβε χώρα το 2022 στη Βαλένθια, ενώ για την ανάδειξη των συστημάτων αυτών ως εργαλεία λήψης απόφασης, μελετήθηκαν δημοσιεύσεις της ερευνητικής ομάδας συνεργασίας του ETH και του Πολυτεχνείου του Μονάχου, που ασχολούνται με συστήματα λήψης αποφάσεων για τις κατασκευές και τις υποδομές.

Από την ανωτέρω ανάλυση προέκυψαν τα εξής συμπεράσματα: κύριοι λόγοι παρακώλυσης της ευρείας αξιοποίησης των συστημάτων παρακολούθησης σε πρακτικές εφαρμογές είναι το κόστος των συστημάτων και η απροθυμία των κυρίων των έργων να επενδύσουν σε αυτά τα συστήματα. Λύση σε αυτό το πρόβλημα αποτελεί το πλαίσιο της αξίας της πληροφορίας, μέσω του οποίου ποσοτικοποιούνται και μεταφράζονται σε χρηματικές μονάδες τα οφέλη των ενόργανων συστημάτων. Εκτός από τους παραπάνω λόγους υπάρχουν ακόμα και τεχνικά/υπολογιστικά εμπόδια. Λύση σε αυτά δίνουν οι νέες τεχνολογίες, μέσω των οποίων καθίσταται δυνατή η παρακολούθηση σε απρόσιτα και επικίνδυνα σημεία, η αυτόματη παραγωγή αποτελεσμάτων μέσω προηγμένων αλγορίθμων, η αποδοτικότερη διαχείριση δεδομένων και η ενίσχυση της επικοινωνίας των ενδιαφερόμενων μερών. Όσον αφορά την Ελλάδα, παρατηρήθηκε ότι δεν υπάρχουν σαφή, δεσμευτικά πρότυπα με τα συστήματα παρακολούθησης μεγάλων τεχνικών έργων να παρουσιάζουν ανομοιογένεια, η οποία εν μέρει θεωρείται λογική λόγω των ιδιαιτεροτήτων των έργων. Παρόλα αυτά, μέσω των παραδειγμάτων μελέτης επιβεβαιώνονται τα θεωρητικά διατυπωμένα πλεονεκτήματα της παρακολούθησης. Τέλος μέλλον των συστημάτων αυτών αποτελούν τα «πληθυσμιακά συστήματα παρακολούθησης» που εκμεταλλεύονται τις ιδιότητες της μηχανικής μάθησης

και χρειάζονται μικρότερο αριθμό δεδομένων εκπαίδευσης. Ωστόσο για την εφαρμογή των συστημάτων αυτών απαιτείται ενσωμάτωση των νέων τεχνολογιών στη διαδικασία της παρακολούθησης και καθορισμός σαφών και αναλυτικών προτύπων, ώστε να διασφαλιστεί η ποιότητα των απαιτούμενων δεδομένων.

Η εργασία επομένως παρουσιάζει την ενόργανη παρακολούθηση ως μία ολιστική μέθοδο και όχι απλά ως μία τεχνολογία, γεφυρώνοντας το χάσμα μεταξύ της τεχνικής και διαχειριστικής πτυχής των συστημάτων αυτών, συμβάλλοντας έτσι στην ανάδειξη της παρακολούθησης ως ένα πολύτιμο εργαλείο αποδοτικότερης διαχείρισης έργων.

Abbreviations

AI	Artificial Intelligence
BIM	Building Information Modelling
DEM	Digital Elevation Model
DT	Destructive Testing
EOSA	Egnatia Odos S.A
FEM	Finite Element Model
GNSS	Global Navigation Satellite System
ID	Influence Diagram
IoT	Internet of Things
ML	Machine Learning
NDT	Non-Destructive Testing
PBSHM	Population Based Structural Health Monitoring
RUL	Remaining Useful Life
SHM	Structural Health Monitoring
SPRP	Statistical Pattern Recognition Problem
UAVs	Unmanned Aerial Vehicles
VoI	Value of Information
VoS^2HM	Value of Seismic Structural Health Monitoring
VoSHM	Value of Structural Health Monitoring

1. Introduction

Europe is dealing with an ageing infrastructure inventory and restricted resources for maintenance and restoration. Apart from natural ageing, structures' state is at stake due to extreme weather events caused by climate change phenomena (https://climate.ec.europa.eu). Moreover, additional damage inducing factors act upon structures. In general, structures are deteriorating due to:

- ageing and fatigue (Giordano, et al., 2023),
- loads greater than the design loads
- environmental factors and variations (Giordano, et al., 2022)
- emergency and extreme events (Giordano, et al., 2020)
- poor maintenance

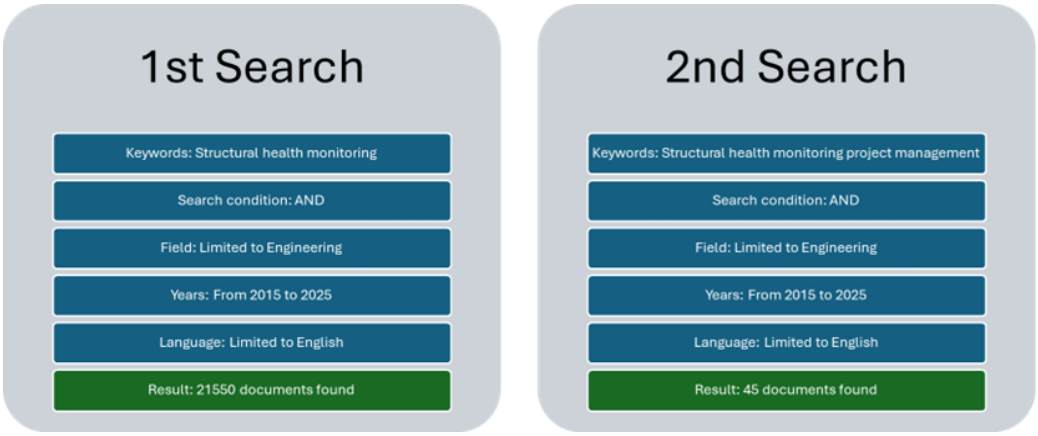
From aforementioned deterioration factors, some are endogenous and can be controlled by appropriate and effective project management, while others are exogenous and cannot be controlled. Among endogenous factors, poor maintenance is identified. Monitoring systems offer exceptional opportunities for enhanced maintenance management. SHM is the process of implementing a damage detection strategy (Farrar & Worden, 2007), while deformation monitoring is a displacement detection method (Alevizakou, 2017). Other well known and commonly implemented techniques which are characterized by high intervention or qualitative nature are out of the scope of work of the present thesis. By implementing a quantitative monitoring system, owners can gain serious profits. Apart from enhanced safety management, which is first priority, other advantages are (Inaudi, 2009; Abdelrazaq, 2011; Cawley , 2018 ; Giordano & Limongelli, 2020):

- Verification of design parameters
- Enhanced cost management as they provide data for informed decisions, which are associated with reduced costs
- Enhanced emergency management, as they offer the necessary information for early warning
- Enhanced risk management, as they offer data for quantitative assessment and reduce uncertainty
- Estimation of RUL and possible extension of asset's life
- Development of a database, whose data can be exploited for more efficient future designs and from already existing similar structures

1.1 Aim of the study

The present thesis aims at (i) identifying current principles, methods and procedures utilized for quantitative monitoring (ii) exploring the potential of integrating innovative technologies in monitoring chain (iii) investigating the current state of monitoring in Greece and (iv) connecting monitoring with project management through a robust decision-making framework. It is noted that monitoring is a scientific field of great research. However, the majority of related publications focuses on technical and computational aspects rather than

managerial. As is displayed in the following figure, significant gap between technical/computational and managerial publications exists. By exploring monitoring's managerial aspects, its value as a decision-making tool is highlighted. Thus, this study aims at bridging this gap by covering technical and managerial issues and considering monitoring as a holistic approach.



1.2 Study method

For achieving the aforementioned objectives literature review and bibliographic research are performed. Main reference sources were Scopus database and Google Scholar. For investigating the detailed decision-making framework, publications from ETH's research group and action TU 4012 were explored. Publications regarding the implementation of new technologies for monitoring applications were found from the proceedings of the 5th JISDM, which took place in Valencia, 2022. Additional sources such as books and lecture notes were utilized as well.

1.3 Study Structure

A brief description of study's structure is presented.

- In chapter 2 some key core definitions are presented and distinction between common monitoring techniques is addressed.
- In chapter 3 the traditional methods for monitoring man-made structures are presented. These are the geodetical and geotechnical methods.
- In chapter 4 fundamental aspects of SHM are presented. Emphasis is given to the current state of SHM while parameters defining an SHM system are analyzed. In this chapter major challenges hindering SHM wider adoption are addressed as well.
- In chapter 5 the potential of integrating new technologies is investigated. Major technologies of Construction 4.0. are described and research works utilizing these technologies are explored
- In chapter 6 a detailed decision-making framework is presented which accentuates the value of exploiting monitoring outcomes for data-driven management.

- In chapter 7 case studies are presented in order to assess current SHM state in Greece. 5 major types of infrastructure projects are explored. When sufficient and reliable information was unable to be found, case studies from abroad were analyzed.
- Finally, in chapter 8 the conclusions reached after the above study are addressed.

2. Theoretical background

In this chapter, key core definitions are provided. Definitions of fundamental aspects are considered necessary both for facilitating the reader and for further clarifying the limits of the scope of this thesis.

2.1 Structural Health Monitoring & Deformation Monitoring

SHM is a scientific field of great importance and big interest, and more detailed definitions have been provided through the years. Based on (Farrar & Worden, 2007;. Wilson , et al., 2018; Sohn, et al., n.d.) SHM is a method for damage detection of structures. The same definition can be identified in (Abdo, n.d.) review book. Balageas, et al. (2006) define SHM as a means of "diagnosis" for the already existing damage, and of "prognosis" for future damage. Guemes, et al. (2020) give a more specific definition based on a SAE Standard. SHM is a method for collecting and processing data to assess the structure's state. The latest approach regarding SHM is defined by Farrar, et al. (2024). The key core definition, that SHM is a damage detection methodology remains, but the methodology is defined in greater detail as a *"quantitative, autonomous, online and in situ monitoring methodology, applicable on a more global scale"*. Although, details of the first SHM implementation are not known, Brownjohn (2007) states that instrumental monitoring systems with the capability of data evaluation began to be utilized after the middle of the 20th century. Some of the first structures for which the implementation of such systems was compulsory by law are dams (Brownjohn, 2007).

In the same fashion, there is deformation monitoring. Deformation monitoring refers to the continual process of detecting displacements both for man-made structures and natural ones (Pantazis, 2020). Geodetic deformation monitoring is carried out by investigating the displacement of discrete points located on an object (Alevizakou, 2017). Survey engineering is a field that contributes to the development and evolution of deformation monitoring. A timeline (Figure 1) of the major events related to the development of geodetic deformation monitoring is presented below.

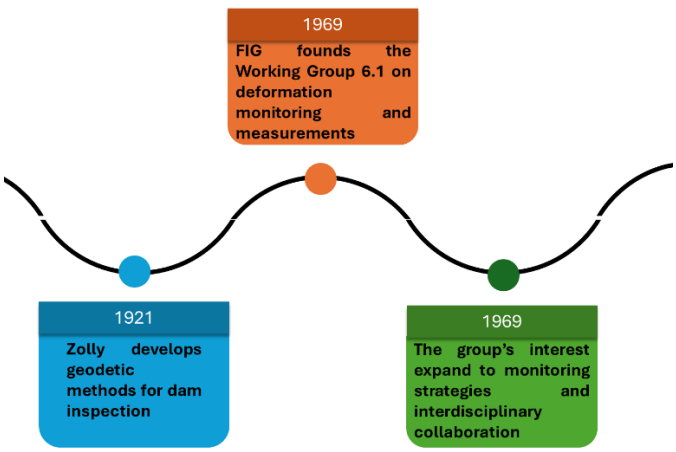


Figure 1: Timeline of major events regarding deformation monitoring

The terms mentioned are interrelated and certainly both concepts refer to the field scientifically known as ***monitoring*.** Throughout the years, monitoring systems and schemes were implemented in major infrastructure projects.

2.2 Additional definitions

Apart from the two fundamental terms mentioned above, additional definitions are provided in this chapter. Source of these definitions are (Mufti, et al., 2003; Agatza Balodimou & Panou, 2018 ;COST TU 1402, 2019 ; Pantazis, 2020 ; Alevizakou, 2017 ; The Welding Institue, n.d.).

Condition assessment	Estimating the structure's current state and forecasting its future state based on acquired information
Damage	Alterations which negatively affect a structure's performance
Deformation	Change of the form of an object's surface, due to the position change of a set of point
Displacement	Change of position of a single point
Epoch	The time at which measurements take place
Geodetic Network	A set of points located on an object and interconnected with geodetic measurements
Measurement accuracy	Level of closeness of measurements to their true value
Measurement precision	Level of closeness of the measurements to each other
Measurement reliability	The combination of accuracy and precision
Network sensitivity	The minimum value of a quantity that the network can detect
Redundancy	Existence of redundant measurements, i.e. more measurements are available than those required to compute the system's variables
Resolution	The minimum value of an observed quantity that a sensor can detect
Sensor	Special equipment measuring parameters by linking the physical parameter and electric-optic parameters
Structural integrity	Structure's ability to function efficiently when loads are acting on it and to maintain its functionality and serviceability without major deformation
Systematic errors	Errors whose values present consistency and can be modelled through a mathematical relationship

Time – series	A set of measurements captured over a period of time

In the following chapters the terms of destructive testing, non-destructive testing and visual inspection are described and distinguished from SHM.

2.3 Destructive and Non-Destructive Testing

Timely detection of damages or abnormalities is of great importance for enhanced safety and efficient operation. Two of the main categories of testing techniques used for condition assessment are destructive and non – destructive testing. Based on their names someone could define DT as the process of condition assessment which induces damage to the structure, while NDT does not. According to Mohsin (2017) DT is a method for structural assessment that causes geometry changes to the materials of the structure. These changes need to be restored after test's completion. On the other hand, NDT is a method for assessment without causing damage or adversely influencing the structure. Apart from the differences in the testing procedure, the results of the two techniques vary. DT directly determines mechanical properties of the material, unlike NDT. Therefore, with NDT appropriate mathematical formulas are required to secondarily determine material properties (Santini, et al., 2020). However, DT cannot be used in specific types of structures, i.e. structures that have been classified as monuments of cultural heritage (Pallarés, et al., 2021). Some of the most common DT and NDT are the following (Mohsin, 2017; Kot , et al., 2021; Pallarés, et al., 2021):

- Core cutting: This is a destructive technique used to test the compressive strength of the concrete by testing an extracted concrete specimen (DT).
- Reinforcement disclosure: By removing a layer of concrete, the reinforcement's condition can be assessed (DT).
- Pull-out: A metal element is inserted into the concrete. The force needed to pull – out this element is related to the concrete's strength (DT).
- Rebound hammer: Using special equipment called rebound hammer, the concrete strength can be evaluated based on the hammer's reading, which is called rebound number (DT).
- Windsor probe testing: A steel probe is inserted into the concrete element and based on the depth that reaches, the concrete's strength can be realized (DT).
- Ultrasonic tests: A transmitter and a receiver are installed on a concrete element. The transmitter releases an ultrasonic wave. Based on the wave's velocity, the material's state can be estimated (NDT).
- Ground Penetrating Radar: It has the same philosophy as ultrasonic tests. A transmitter releases a microwave and a receiver captures it (NDT).

Additionally, Preethichandra, et al. (2023) mention the following sensoring techniques:

- Mechanical sensors: Mechanical sensors' operation is based on the deliberate cause of an impact and the receival of the reflected wave. A special device, the impactor, is imposed on the structure. This procedure produces waves, which are transmitted through the material. The reflected wave is then received by a piezoelectric sensor and transformed into a signal. "Travel time" of these waves is examined in order to come to conclusions regarding the internal properties of the material (NDT)
- Laser sensors: The fundamental basis of operation of laser sensors is the emission of laser pulses, which "travel" through the atmosphere and when they impinge on an object are reflected. The distance between the sensor and the object is computed, as the speed of light is constant and the time the pulse was emitted and received known. The result of this procedure is a cloud of points employed for the 3D representation of the structure which can be utilized for surface damage detection.(NDT)

Even though SHM is non-destructive based on the way it is applied and the level of intervention in the structure, it is not an NDT technique. However, some NDT techniques such as monitoring with ultrasonic, fiber optics, mechanical and laser sensors are used in SHM as well (Kot , et al., 2021). Table 1 displays some key core differences of SHM and NDT.

Table 1: Key differences between SHM and NDT

	SHM	**NDT**
Time	Periodic and continuous	Periodic
Scale	Local and Global	Local
Outputs	Damage sensitive features, abnormalities, geometries, frequencies	Physical Properties
Scope	Time - based condition assessment	Current state
Equipment	Permanent installed sensors	Portable equipment
Autonomy	Potential for fully autonomous systems	Not autonomous

It is also worth mentioning that prior knowledge about the location of the damage is required for NDTs (Farrar, et al., 2024).

2.4 Visual Inspection vs Monitoring

One of the most common ways to detect damages on structures is via visual inspections. Visual inspections can be classified into different categories based on frequency, proximity to the structure and the inspector's experience. According to Egnatia Motorway's inspection manual, there are different types of visual inspection across the world. The categories most commonly encountered are presented in Figure 2

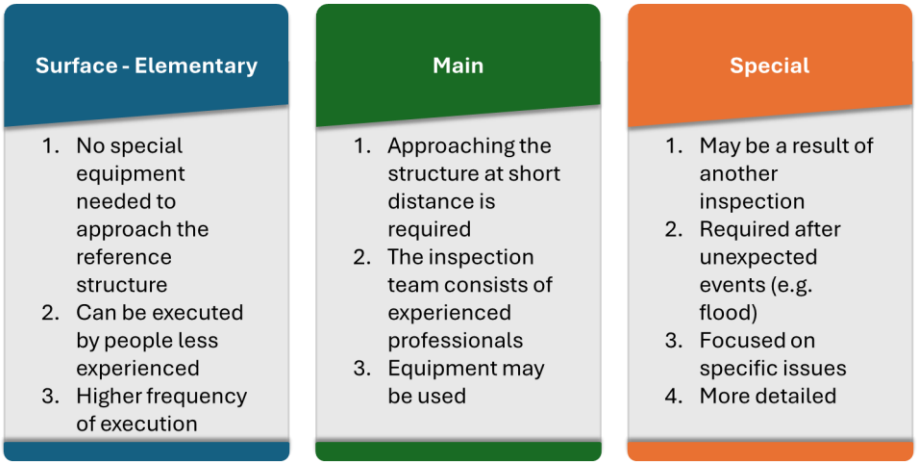


Figure 2: Inspection classification

A similar categorization can be found in the work of Quirk, et al.(2017). They mention that a management system for bridges has three types of visual inspection (i) a more general one for an initial condition assessment, (ii) the principal which is after the initial one and (iii) the special which is more detailed and may require specialized equipment.

Egnatia's manual also highlights the importance of an inspection plan. Briefly the basic steps of a visual inspection are the following:

- Inspection plan: Inspection plan should give answers to some simple but fundamental questions about the procedure,
    - *Where will the inspection take place?*
    - *Which specific structural elements will be inspected?*
    - *Which will be the sequence of the inspection?*
    - *How much time is needed?*
- Preparation: During preparation step, all useful information that will facilitate the inspection procedure is gathered. Drawings, design details, specifications and results of previous inspections are some examples of information that can be utilized during this step. Furthermore, the inspection team will have to decide on the equipment that will be used during inspection.
- Inspection: It is the step where action takes place. The inspection team closely examines structural elements of the whole structure, based on some kind of categorization. The team reports the observed damage and keeps a record of the carried-out measurements (if any). Evidence in the form of photographs or drawings is of paramount importance.
- Evaluation: After the preparation of the inspection report, evaluation of structure's state follows. The final assessment will be based on a scoring system. If the score value is low, the structure is in poor state.

- Repair and response measures: For structures with the most adverse score, countermeasures should be proposed and implemented, based on economic criteria as well.

The procedure described above is straightforward and is the one mostly used for damage identification and assessment (Giordano & Limongelli, 2020). Despite their lower cost and direct nature, visual inspections present some disadvantages (Quirk, et al., 2017; Giordano, et al., 2020; Chadha, et al., n.d.):

- Accessibility dependance: To obtain useful information, close examination is required but it may not be possible due to accessibility issues.
- Subjectivity: There is a possibility that the result is not completely objective, and the decision made may be influenced by the risk profile of the inspector. However, for this reason a team of three members executes the inspection.
- Accuracy: Measurements and outcomes of inspection are less accurate
- Timing: As mentioned in the national manual for bridge inspection, safety of people executing the inspection must be always ensured. That means that inspectors cannot access the structure, not only during extreme events, but even after their occurrence due to adverse site conditions. As a result, critical information about structure's state, right after the occurrence of a deteriorating event, cannot be obtained.

Even though some researchers present visual inspections as one SHM method (Visual SHM) (Brownjohn, 2007), for the present thesis a distinction is made between these two concepts. One of the main reasons for this distinction is to highlight the difference in the decision-making process, from experience-based to data-driven decisions.

2.5 Monitoring and construction project management

Apart from being a popular scientific topic, monitoring can directly enhance the whole construction procedure. Considering design, construction and operation, major project phases, monitoring can provide the required information for each step. More specifically:

- Design: Establishing a monitoring system and acquiring monitoring data, may lead to reevaluation of design parameters (Encardio Rite, n.d.). Furthermore, data acquired from structures function as basis for improved designs of similar structures (Inaudi, 2009; Li, et al., 2015)
- Construction phase: Establishment of an appropriate monitoring network is of paramount importance to ensure the requested quality and the accuracy of the construction, e.g. verify the correct geometry (Niemeier, 2006). Furthermore, for specific types of projects, i.e. tunnelling, monitoring networks are established to ensure safety and to warn in case of abnormal activity (Mooney, et al., 2016). Examples of monitoring during construction are presented by Karamitsos, et al. (2006) and Abdelrazaq (2011).

- Operation & Maintenance: The benefits of a monitoring system are mostly realized during operational phase. Information provided by monitoring systems facilitates the condition assessment procedure, since reliability is enhanced and uncertainty is reduced, and hence repair actions and mitigation measures are considered more effective and efficient. Information from monitoring systems is also of paramount importance during emergency events, allowing for quick and real time response in order to guarantee the safety of the users (Limongelli, 2020).

3. Traditional monitoring methods

Traditionally, two major methods are used for monitoring of infrastructure projects, geotechnical and geodetic methods. In this chapter these two categories are analyzed.

3.1 Geotechnical monitoring

3.1.1 Geotechnical monitoring plan

For successful structural assessment a monitoring plan has to be prepared. Due to unique structure properties and site conditions, monitoring plans are tailored to the respective structure. Briefly, major parts of a monitoring plan are presented bellow.

3.1.1.1 Prerequisites

In order to produce an appropriate monitoring plan a-priori knowledge is required. Among the information required are geological conditions of the area, construction methods, risks associated with possible damage and warning thresholds (Tompoulidou, 2013).

3.1.1.2 Instrumentation plan

The monitoring plan should give answers to major questions associated with instrumentation. Those regard the:

- Type of instrumentation
- Number of instruments
- Location of instruments
- Frequency of measurements

Answers to these questions are provided after the definition of the parameters for which monitoring is essential (Georgopoulos, 2021).

Regarding the selection of instruments additional criteria need to be considered (Tompoulidou, 2013; Georgopoulos, 2021; Sdonas, 2022; Tzanni, 2023):

- Associated cost
- Technical characteristics (range, accuracy, reliability, vulnerability to external factors)
- Data acquisition and transmission time

Moreover, possible parameters affecting observations need to be taken into consideration for accurate assessment of measurements. After the completion of the instrumentation plan, measurements are executed. Data obtained from the measurement procedure are then appropriately analyzed to assess the structure's state and characterize it based on the warning thresholds. The outcome of the whole procedure is a data-driven mitigation plan (Georgopoulos, 2021).

3.1.2 Instruments

Since the core of the monitoring plan is instruments, in this chapter some common geotechnical instruments, utilized for monitoring applications, are presented.

3.1.2.1 Piezometers

Piezometers are devices that measure the pore water pressure (Georgopoulos, 2003 ;. Encardio Rite, n.d.; ELOT, 2009). They are installed at certain depths in soil, rock or concrete elements. These devices are utilized in major infrastructure projects to assess the level of groundwater and the stability of the observed object. Extensive use of piezometers is done in dams for monitoring common issues, such as piping and seepage (Encardio Rite, n.d.).

Various types of piezometers exist, such as observation wells, open standpipe piezometers and closed type piezometers (Tompoulidou, 2013). A common type of piezometer is the vibrating wire piezometer. The sensor system consists of a stretched wire connected to the instrument. Water pressure changes cause the wire to vibrate with different frequence. These frequence deviation is recorded via electrical signals (Precision Drilling Australia, n.d.).

Based on technical specification 13-05-07-00 (ELOT, 2009), technical characteristics which need to be considered are displayed in Table 2

Table 2: Piezometer characteristics

Characteristic	**Description**
Range	The range of values the instrument is able to observe
Precision	
Sensitivity	Sensitivity is expressed here as resolution, i.e. as the minimum value the instrument is able to observe
Filter	

3.1.2.2 Inclinometers

Inclinometers are devices which can be placed inside drillholes and utilized for measuring transversal deformations (Georgopoulos, 2003 ;Roussou, 2007). Inclinometers are classified as either horizontal or vertical inclinometers (Xistris, 2015). The probe containing the sensing devices is connected with a wire to the final readout device. Deviation from the system's reference axis is recorded as deformation. Vertical inclinometers capture horizontal displacements, while horizontal inclinometers capture vertical displacements. Common applications include monitoring retaining walls, tunnels, earth dams and events such as landslides (Tompoulidou, 2013). Components of inclinometers are the probe and special casting, the wire and the read-out device. Probe contains the sensors recording the angle difference between the reference axis and the current probe axis. Measurements recorded as electrical signals are transmitted with the help of the wire which is connected with the read-out device (Tompoulidou, 2013).

3.1.2.3 Strain gauges

Strain gauges are measuring devices capturing deformations when placed on objects of interest. According to Hellenic National Specification 12-08-02-00 (ELOT, 2009), the three main types of strain gauges are:

1. Electrical resistance strain gauges: Main component is a metallic foil or a setup of semiconductors (ELOT, 2009). The basis of their function is that when placed under stress the gauge presents altered geometry and thus altered resistance. This change is captured and transformed into strain. An advantage of these devices is their low cost, however they have drawbacks associated with their temperature vulnerability and the fact that they are unsuitable for objects which tend to present cracks (ELOT, 2009).
2. Vibrating wire strain gauges: These types of strain gauges can be embedded on the structure's elements or welded onto them. The embedded strain gauges are suitable for concrete and soil elements, while the weldable strain gauges are suitable for steel elements. The wire of the strain gauge is stretched and vibrates with a certain frequency. Under loading the wire vibrates with a different frequency. Strain is then computed as the square of the recorded frequency (GeoInstruments, n.d.)
3. Optical fiber strain gauges: Optical fiber strain gauges are a promising monitoring technology. Bragg fiber optic sensors have been successfully used at bridge applications. Their function is based on the wavelength alterations of light signals. The wire is constructed in a way that the wavelength has a specific value. Under tension the wavelength of the light signal changes. Investigating the wavelength's alterations defines the strain of the structure (Lin, et al., 2025).

3.1.2.4 Tiltmeters

Tiltmeters are equipment capturing rotation changes in relation to their placement. The instrument consists of a sensor measuring tilt, which is incorporated into a frame (Georgopoulos, 2003). Their applications are wide including dam, tunnel, retaining wall and bridge monitoring and monitoring under emergency events such as landslide (Pantazis, 2020).

3.1.2.5 Accelerometers

Accelerometers are devices measuring dynamic properties of structures (ELOT, 2009). Accelerometers can detect acceleration forces in 3 dimensions, which provides useful insight regarding structure's dynamic properties (Pantazis, 2020). Common types of accelerometers are the following (EPSON, n.d.):

- Piezoresistive
- Servo-type
- Piezoelectric
- Capacitive
- Frequency-change

Accelerometers are utilized for structural monitoring, while they are also a powerful tool during extreme events, e.g. earthquakes.

3.1.2.6 Extensometers

Extensometers are devices which can be placed inside drillholes and utilized for measuring deformations parallel to a reference axis (Tompoulidou, 2013). If they are placed vertically, they capture vertical displacements, whilst if their placement is horizontal they capture

horizontal displacements. Vertical placement is used for monitoring underground projects, foundations, embankments etc, while horizontal placement could be used for crack growth monitoring (Georgopoulos, 2003). Two types of extensometers are (i) the rod extensometers and (ii) magnetic extensometers (Xistris, 2015).

Apart from the aforementioned instruments, there are other geotechnical sensors utilized for monitoring. It is worth mentioning that Technical Chamber of Greece has provided a detailed manual with guidelines regarding experimental monitoring. More specifically it includes basic principles, methods, instruments and examples of instrumented structures.

3.2 Geodetic monitoring

The second traditional monitoring method is geodetic monitoring and more specifically geodetic monitoring networks. An initial definition of geodetic network is provided in chapter 2. Based on that definition, a geodetic network is a set of points. Diving into more detail these points are:

- Monitoring/ Control points: Set of points placed on the structure under monitoring, at locations which are more likely to be deformed
- Reference points: Set of points around the structure, and out of the impact radius of the phenomena which causes the deformation. In general, these points are located on stable and less likely to be deformed areas

3.2.1 Types of networks

Before further analysis is performed, it is considered essential to present a classification of geodetic monitoring networks based on dimensions and adjustment type:

3.2.1.1 Dimensions

One of the major classifications of geodetic networks is based on their dimension (Lambrou & Pantazis, 2011; Georgopoulos , 2017; Agatza Balodimou & Panou, 2018; Pantazis, 2020). More specifically, according to the type of movement the network has been designed to detect, three major categories arise:

- 1D networks: Vertical movements are detected
- 2D networks: Horizontal movements are detected
- 3D networks: Both horizontal and vertical movements can be detected

Each network is used in different applications.

3.2.1.2 Adjustment

Geodetic networks can be classified as static and dynamic.

- Static networks: Measurements are executed at different epochs and adjusted independently. The results of the two epochs are used to calculate the deformation vector and then it is assessed whether an actual deformation has occurred (Alevizakou, 2017).

- Dynamic networks: Measurements of different epochs are adjusted simultaneously through one adjustment process. (Pikridas , et al., 2009; Alevizakou, 2017)

Also, another distinction between these two types of networks is that for the static networks the measurements take place at discrete time intervals, while kinematic networks are associated with continuous monitoring. Analysis follows for static and dynamic networks.

3.2.2 Network planning

In this chapter the general framework regarding networks is presented, without distinction between static and dynamic networks. From a managerial point of view, deformation monitoring is a process which is of paramount importance for the safety of the structure and requires its own dedicated design, even during the project's planning phase (US Army Corps of Engineers, 2018). All the aspects regarding the monitoring network should be presented within the monitoring plan of the specific structure. The following graph (Figure 3) depicts all aspects covered by a monitoring plan (US Army Corps of Engineers, 2018), which are analyzed in detail afterwards.

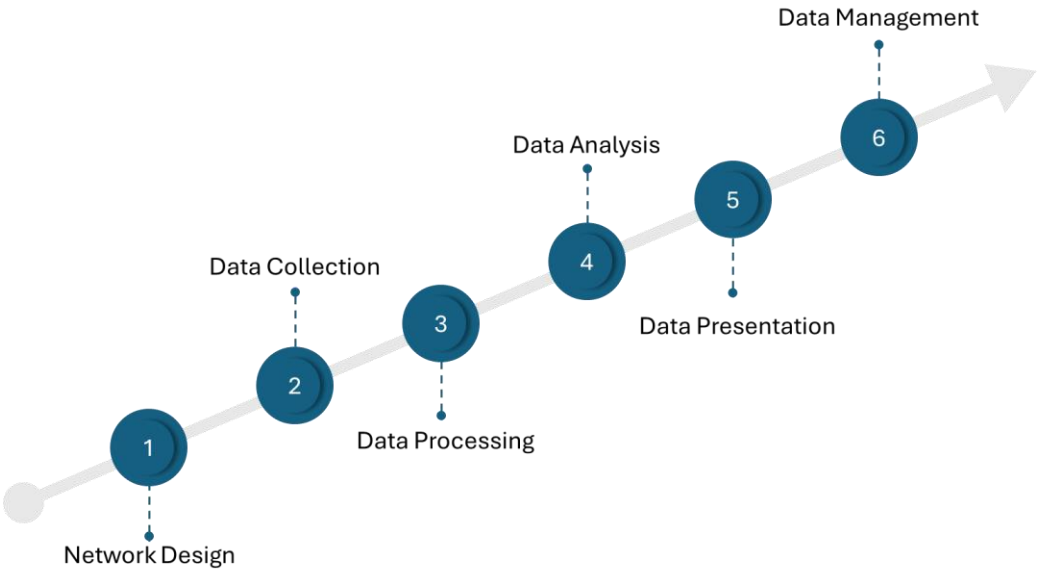


Figure 3: Geodetic network lifecycle

Network design: During network design two different plans are created, the measurement plan and the instrumentation plan. The instrumentation plan covers in full detail issues related to network points (control and reference) which will be installed. In particular, it includes necessary information about the location of the points, marking methods (types of pedestals), maintenance of the pedestals, etc. In the measurement plan everything regarding measurements is specified. First of all, the accuracy to be achieved is decided. Moreover, the type and number of measurements are defined together with the type of instruments that will be used to achieve the required accuracy. Furthermore, the mathematical formulas used to convert the raw data into coordinates are specified. Finally, issues regarding storage of both the raw data and the final coordinates are discussed.

During this step, the so-called network pre-analysis takes place. It can be said that one of the most important aspects of this pre-analysis is the optimization of the network. The result of the optimization process is the final network design with most effective combination of measurements, instruments and network points in terms of cost and accuracy.

The steps 2 – 6 are fully described in the plans mentioned above.

Data Collection: During data collection, monitoring team performs all the measurements defined in the measurement plan. The aspects covered in measurement plan for the data collection stage aim at achieving reliable observations. As a result, issues regarding equipment checking procedures before measurement execution, methods of measurement and on-site measurement checks need to be discussed. The outcome of this stage is reliable raw data.

Data Processing: During data processing, the raw data collected during the previous stage is converted into useful information. Therefore, the measurement plan should cover issues regarding the data filtering procedures, with which possible wrong observations are defined as outliers and excluded from the calculation process so as not to degrade the overall accuracy, and mathematical relationships which will be used for the calculation of the results. The outcomes of this stage are the final coordinates of the network's points.

Data Analysis: During this stage the coordinates calculated during previous step are exploited to determine the deformation vector. The magnitude of the vector is easily calculated as a coordinate difference. The final assessment of whether the vector is a deformation is done after statistical analysis. Therefore, the plan should cover issues regarding confidence level and statistical distributions. Apart from that for 2 and 3 dimensional networks, the tests with which the final decision will be made have to be defined. Outcomes of this stage are the displacement vectors along with the assessment whether they are deformations.

Data Presentation: Although this stage may not seem of great significance, it should nevertheless be covered in the monitoring plan mainly because the stakeholders are not always familiar with the procedures of measuring, calculating and evaluating the results. Therefore, the plan should cover issues regarding technical reports describing the overall procedure and the format of the results. The outcome of this stage is a technical report which clearly depicts the measuring, calculating and evaluating procedure and provides mitigation measures that should be employed if required.

Data Management: During this stage all the data, information and results produced during the above steps are stored and maintained. Due to the fact that monitoring is a long-term procedure, the appropriate storage and retrieval of raw data and calculated results is extremely important to enable the identification of deformations. Therefore, the plan should cover issues regarding the type of data which will be stored, the location of data, and the time that this data will be available. Outcome of this stage is an enriched database.

3.2.3 Static networks

In this chapter, static geodetic networks are described.

3.2.3.1 Type of measurements

Based on the type of network, different measurements are executed. More specifically (Georgopoulos , 2017):

- 1D: Observations are height differences
- 2D: Observations are horizontal and vertical angles and distances
- 3D: For terrestrial networks the measurements mentioned above are executed while for satellite networks satellite observations are executed

3.2.3.2 Instruments

Considering the above, it is evident that the selection of the equipment depends on the type of network and consequently on the measurements which will be carried out (Pantazis, 2020).

- For 1D networks the most commonly used equipment nowadays is the digital level along with its accessories.
- For 2D networks the most commonly used equipment nowadays is the total station with its accessories.
- For 3D terrestrial network a combination of the above equipment can be used, while for satellite networks GNSS receivers are exploited.

3.2.3.2.1 Digital leveling equipment

As mentioned above, digital leveling equipment is the most employed for 1D network applications. Apart from the digital level itself, for the measurement procedure some accessories are required. The accessories are the leveling rods or staff, which are displayed in Figure 4.

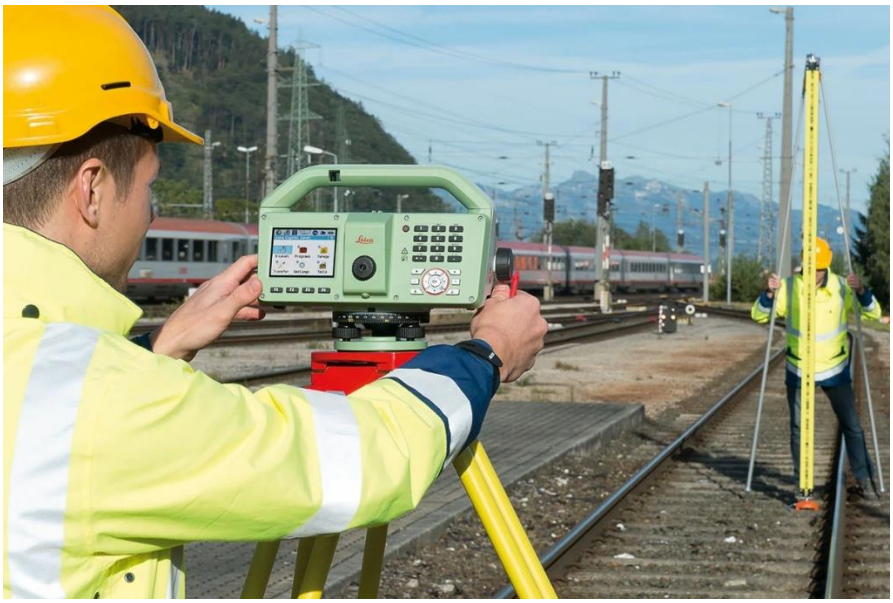


Figure 4: Digital level and barcoded staff (https://www.onepointsurvey.com/)

Digital levels are instruments whose main observations are height differences. Two of their most important parts are the telescope and the CCD camera. The fundamental function of

the digital level is the following. The observer aims through the telescope at the center of the coded staff. If the aiming is considered satisfactory the observer proceeds with the measurement. The measurement is ultimately an image capturing procedure of the visible part of the staff's code. The image is then processed and compared to a standard code stored in the instrument and after appropriate processing the measurement is displayed on the instrument's screen. As other procedures based on image capturing, a source of light is required. As a result, the lighting conditions may pose some difficulties and affect the accuracy of the measurements. Heterogeneous lighting and shaded areas are some common difficulties. Other issues regarding digital leveling are vibrations and atmospheric effects, which influence the results as they cause a deviation of the line of sight from the normal position. Apart from that, the cost of the digital levels is higher than other similar instruments such as the optic levels. However, the simple and quick procedure along with the high accuracy are some of the advantages of the method and thus geometric leveling is considered one of the most preferred methods for measuring 1D monitoring networks (Ingensand, 2000; Lambrou & Pantazis, 2011; Georgopoulos , 2017).

Regarding the selection of the most suitable instrument, apart from cost, a set of aspects needs to be taken into consideration. In the following table, some key factors for the selection are displayed (Table 3), based on Leica LS Digital levels data sheet.

Table 3: Technical characteristics of digital levelling equipment

Parameter	**Description**
Accuracy	The nominal accuracy of the instrument. The selected instrument should have the accuracy needed to achieve accuracy requirements of the specific monitoring applications
Range	Minimum and maximum operational distance. Both these distances are factors affecting the instrument selection. Based on the geometry of the network, the instrument's range should be examined
Cost	Instruments cost, both for purchase and for maintenance and repair
Weight	Instrument's weight is an important factor when the network includes many points and great distances. Weight may be a factor affecting the crew's productivity
Autonomy	Instrument's battery duration is considered as autonomy. This aspect may affect the measurement campaign duration and time schedule
Dust and water resistance	Monitoring applications take place in harsh environments and under adverse site conditions. For this specific application the resistance of the instrument and its ability to operate under adverse conditions are major aspects
Operational conditions	

3.2.3.2.2 Total stations

Total stations are instruments measuring simultaneously angles (horizontal and vertical) and distances, and they are the evolution of digital theodolites and EDMs. The combination of these two instruments along with a computer device compose the total stations. For measurements to be reliable, the fundamental principal of function of total stations must be satisfied: the main axis of the instrument must be vertical, the secondary axis must be perpendicular to the main axis and the axis of the line of sight must be perpendicular to the secondary axis. For the execution of measurements additional devices and equipment are required. These devices and equipment are tripod, reflector and tribraches. Tribrach adapts to the tripod and then the instrument adapts to the tribrach. Tribrach is required to ensure appropriate placement of the instrument in order to satisfy the fundamental principal of function and to be centered above the respective point. Reflector is used for distance measurements. A pulse is emitted by the instrument, reflected by the reflector and captured again by the instrument. Since the time of emission and recapture are known and the speed of light is considered constant, the distance can be computed (Georgopoulos, et al., 2011; Lambrou & Pantazis, 2011; Georgopoulos , 2017).

Accessibility between points of a monitoring network is not always easy or even possible. Thus, total stations with the capability of measuring distances without reflectors are utilized. The function of these instruments lies upon the emission of a laser pulse which is reflected by every type of surface (Lambrou & Pantazis, 2011; Pantazis, 2021). By utilizing a reflectorless instrument, measurements otherwise impossible to be performed can be carried out, while a second person is not required. However, the distance measurements have higher uncertainties as the result is affected by the properties of the surface, lighting conditions, laser quality, distance etc. (Pantazis, 2021). Finally, some special types of total stations exist with enhanced capabilities (Lambrou & Pantazis, 2011; Pantazis, 2021). Some of these types are presented in the following table (Table 4):

Table 4: Types of total station with additional capabilities

Type	Description
Automatic target recognition	Total stations with this ability have an incorporated CCD camera. A laser pulse is emitted and reflected back by the reflector. By comparing the trace of the laser pulse and the center of the cross-line of the telescope, slight movements of the instrument are performed. If the target is within the central 1/3 of the instrument's vision, then target recognition is done by performing a spiroidal movement. Another advanced capability is the tracking of the target. After the initial target lock and first measurement, as described above, the instrument has the ability to track the moving target.
Robotic	Robotic total stations have the ability to be controlled remotely due to the communication system of radio-modem

Imaging	Total stations with this ability have an incorporated CCD camera. The picture through the telescope is presented by the instrument's screen for enhanced measurements in terms of precision. Spatial imaging stations have an additional camera attached on them for scanning surfaces

Regarding the selection of the appropriate instrument, apart from cost, the following parameters are considered (Table 5) based on Leica Nova TS60 data sheet.

Table 5: Technical aspects of total stations

Characteristic	**Description**
Angle accuracy	Accuracy of horizontal and vertical angles
Distance accuracy	Accuracy of distance measurements with and without prism and the time associated with these measurements. For non-prism measurements the laser quality is also considered
Computer properties	Operating system, processor, display and keyboard, data storage
Energy properties	Battery properties, autonomy time
Weight	Instruments' weight is an important factor when the network includes many points and great distances
Operational conditions	Temperature range, resistance to dust and water, humidity

It is noted that for ATR and Imaging total stations parameters associated with camera quality, accuracy of target recognition etc. need to be considered as well.

3.2.3.2.3 GNSS Equipment

In order to perform measurements with satellite methods, appropriate devices and equipment are required. These devices are:

- Antennas: Antennas are the devices capturing the signal emitted by satellites. Satellite signal, when received from antennas, is weak. Thus, antennas include a preamplifier device to amplify the satellite signal. Afterwards, the pre-amplified signal is transmitted to receiver (Fotiou & Pikridas, 2012).
- Receivers: Receivers as their name suggests receive the pre-amplified signal for additional processing. Receivers consist of different sectors, which are (i) radiofrequency, (ii) channels with tracking loops, (iii) microprocessor, (iv) power, (v) storage. Pre-amplified signal is processed at RF sector. Result of the process is a signal with lower frequency but same module. Signals are then transmitted to channels. The number of channels corresponds to the number of satellites observed. Tracking loops perform the measurements. Finally, microprocessors are

responsible for all the receiver functions and the real-time position computation (Fotiou & Pikridas, 2012)

- User interface controllers: Controllers are the interface between user and receiver. Through controllers the user defines measurement parameters and receives messages and warnings from the system (Fotiou & Pikridas, 2012).

3.2.3.3 Results

3.2.3.3.1 Data processing

The results of the measuring campaign are raw data. The type of raw data depends on the type of network as mentioned above. Raw data needs to be transformed into something meaningful and broadly understandable. In most geodetic monitoring applications, the results of the computational process are coordinates.

For the computational process the least squares method is employed. For the implementation of the least squares method, equations linking unknown parameters to observations are required. The unknown parameters are the coordinates of the network points, and they form vector $\hat{x}$. The coefficients of the unknown parameters form matrix A, which is called design matrix and observations form vector δl. Due to measurement imperfections there is a quantity υ which represents the difference between the observed measurement and its true value. This quantity is the residual. (Niemeier, 1981; Agatza Balodimou & Panou, 2018;Eteje, 2020). The equation system is the following:

$$A\hat{x} = \delta l + \upsilon$$

Where,

- A: design matrix
- $\hat{x}$: vector of unknown parameters
- δl: observations vector
- υ: residuals

The result of the method is the coordinates of the network points along with their uncertainties.

The adjustment process is followed by a series of statistical tests (Figure 5). These tests are required since realizations have been made during the network's adjustment regarding the functional model (Georgopoulos , 2017). These tests include the overall test, the Baarda's test etc. In case of failure, the model must be re-evaluated (Agatza Balodimou & Panou, 2018; Pantazis, 2020).

The overall test examines whether the network is affected only by random errors and whether the realizations regarding the model are accurate. If the overall test fails, the realizations regarding the model need to be revised, the network adjustment will be reconducted and the result will be evaluated again (Agatza Balodimou & Panou, 2018; Pantazis, 2020).

Baarda's test examines whether gross or systematic errors invade into the observations. If Baarda's test reveals some observations as outliers, then these observations should be

evaluated and possibly excluded from the computational procedure (Agatza Balodimou & Panou, 2018; Pantazis, 2020).

The purpose of these tests is to ensure that the monitoring process relies on sound and reliable data. Consequently, well-grounded assumptions about the structure's state can be made. From a managerial perspective, this translates into timely and more informed intervention and thus reduced costs and safety risk.

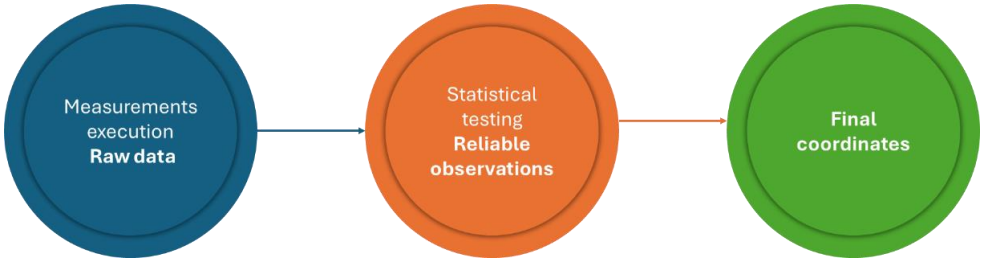


Figure 5: Simplified flow chart of the computation procedure

3.2.3.3.2 Deformations estimation

With the completion of the data processing, the computation of the deformation becomes feasible. In geodetic applications there are three types of deformations, which can be computed, absolute displacements, relative displacements and deviation (Alevizakou, 2017).

- Absolute displacements: The absolute displacement of a point i is the difference of the point's position between epoch t_i and epoch t_{i+1}. More specifically, with the points coordinates known for the current measurement epoch (t_{i+1}) and the reference epoch t_i, the absolute displacement is computed as magnitude of the coordinate differences of the point between the two measurement epochs (Pantazis, 2020).
  - 1D Networks

$$\delta H_i^{(t_i,t_{i+1})} = (H_i^{t_i} - H_i^{t_{i+1}})$$

  - 2D Networks

$$R_i^{(t_i,t_{i+1})} = \sqrt{\left(x_i^{t_i} - x_i^{t_{i+1}}\right)^2 + \left(y_i^{t_i} - y_i^{t_{i+1}}\right)^2}$$

  - 3D Networks

$$R_i^{(t_i,t_{i+1})} = \sqrt{\left(x_i^{t_i} - x_i^{t_{i+1}}\right)^2 + \left(y_i^{t_i} - y_i^{t_{i+1}}\right)^2 + \left(z_i^{t_i} - z_i^{t_{i+1}}\right)^2}$$

- Relative displacements: Relative displacements examine the deformation of point i in comparison to point j of the network, between two measuring epochs. Therefore, the above formulas are transformed respectively (Pantazis, 2020).
  - 1D Networks

$$\delta H_{ij}^{(t_i,t_{i+1})} = \left(H_j^{t_i} - H_i^{t_i}\right) - \left(H_j^{t_{i+1}} - H_i^{t_{i+1}}\right)$$

  - 2D Networks

$$R_{ij}^{(t_i,t_{i+1})} = \sqrt{\left(\left(x_j^{t_i} - x_i^{t_i}\right) - \left(x_j^{t_{i+1}} - x_i^{t_{i+1}}\right)\right)^2 + \left(\left(y_j^{t_i} - y_i^{t_i}\right) - \left(y_j^{t_{i+1}} - y_i^{t_{i+1}}\right)\right)^2}$$

- 3D Networks

$$R_{ij}^{(t_i,t_{i+1})} = \sqrt{\left(\left(x_j^{t_i} - x_i^{t_i}\right) - \left(x_j^{t_{i+1}} - x_i^{t_{i+1}}\right)\right)^2 + \left(\left(y_j^{t_i} - y_i^{t_i}\right) - \left(y_j^{t_{i+1}} y_i^{t_{i+1}}\right)\right)^2 + \left(\left(z_j^{t_i} - z_i^{t_i}\right) - \left(z_j^{t_{i+1}} - z_i^{t_{i+1}}\right)\right)^2}$$

Note: For the 2D and 3D networks apart from the magnitude of the deformation vector, the orientation of the vector is computed as well.

- Deviation

  Deviation is the difference between points located on structural elements for the same epoch (Alevizakou, 2017). It is not applicable to 1D networks.

$$D_{ij} = \sqrt{\left(x_j - x_i\right)^2 + \left(y_j - y_i\right)^2}$$

  For reasons of clarity an example is presented. On the column of Figure 6, two control points are established. As depicted in the shape, the two control points have the same horizontal position and different heights. To ensure safe operating conditions the vertical deviation of the element needs to be examined. If the deviation is greater than an allowable tolerance, then no safe operating conditions are ensured, and the risk of failure occurrence is probable.

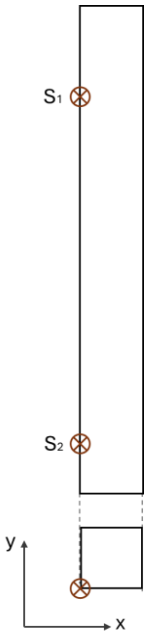


Figure 6: Deviation testing of a column

3.2.3.3.3 Statistical evaluation

The result of the data processing procedure is coordinates of network points. To decide whether there is deformation, statistical assessment takes place.

The basis of the evaluation is the following:

- Null hypothesis H_0: There is no deformation

$$\mu = \mu_0$$

- Alternative hypothesis H_1: There is deformation

$$\mu \neq \mu_0$$

$$\mu > \mu_0 \; or \; \mu < \mu_0$$

The alternative hypothesis testing can be either one – side or two sided. In most monitoring cases the μ is the absolute value of the deformation vector's magnitude. Consequently, in applications related to monitoring, a one-sided hypothesis test is employed (Agatza Balodimou & Panou, 2018). This procedure is known as one-dimensional testing and is applicable in all networks. The μ_0 quantity varies based on the type of network. However, the fundamental principle remains the same. The computed deformation magnitude is compared against uncertainty multiplied by the distribution factor corresponding to the selected confidence level (Agatza Balodimou & Panou, 2018). It is therefore evident that the selection of the confidence level is a key factor for data assessment. It depends on the specific monitoring application, and it should be made in such a way as to minimize the risk of Type I and II statistical errors. More specifically:

- Type I: The null hypothesis is correct but rejected
- Type II: The null hypothesis is false but accepted

As the confidence level increases the probability for Type I error decreases (Figure 7) (Agatza Balodimou & Panou, 2018). The two mostly employed confidence levels are 95% and 99% (Pantazis, 2020). In most cases a confidence level of 95% is selected as a satisfactory level of falsely rejecting the null hypothesis (Farrar & Worden, 2007). In cases where monitoring involves structures with very significant social impacts in the event of failure or rapidly accelerating phenomena, the statistical testing approach becomes even more conservative.

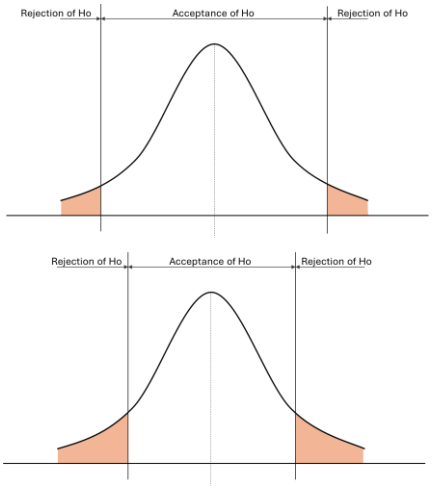


Figure 7: Selection of confidence level

1D Networks

For 1D networks the assessment procedure is the 1D evaluation. Either absolute or relative deformations are computed and afterwords the magnitude of the possible deformation is compared with the following value. The fundamental relationship (alternative hypothesis) is the following:

$$|\delta H_i| > z \cdot \sigma_{\delta H_i{}^{(t2-t1)}}$$

The same procedure is followed if the value to be compared is the relative displacement of the point. For further detail the readers are referred to (Agatza Balodimou & Panou, 2018; Pantazis, 2020)

2D Networks

For 2D networks, 1D evaluation takes place as well. Since the evaluation is performed in two dimensions (x,y) apart from the 1D evaluation, a 2D evaluation is possible by means of error ellipse. The probability density function is now of the form f(x,y) and appears as a bell – shaped surface. The intersection with horizontal planes produces elliptical contours also known as error ellipses (Agatza Balodimou & Panou, 2018). The two axes (σ_{max}, σ_{min}) of the ellipse are computed based on the uncertainty of the coordinate estimation. The calculation formulas can be found in the works of (Agatza Balodimou & Panou, 2018; Pantazis, 2020)

1D Evaluation: In the same fashion as the 1D networks, 1D evaluation refers to the comparison of the absolute magnitude of the deformation vector against the value of the big semi-axis of the error ellipse multiplied by the distribution factor for the selected level of confidence (Pantazis, 2020).

$$|R_i| > z \cdot \sigma_{max}$$

If the above relation is satisfied then there is strong statistical evidence that a deformation has occurred.

2D Evaluation: After the 1D evaluation, a 2D evaluation takes place, employing the error ellipse (Pantazis, 2020). The process of evaluating the presence of deformation using the error ellipse is presented below:

- The semi-axes of the ellipse are calculated along with their respective orientations (Axes a,b and θ angle respectively at Figure 8)
- The error ellipse is produced using the semi-axes appropriately augmented by a factor λ
- The deformation vector is plotted
- If the vector lies outside the limits of the ellipse, then there is strong statistical evidence that the vector is deformation. For example, in the following chart, for the points 3 and 4 a deformation occurrence took place (Figure 9).

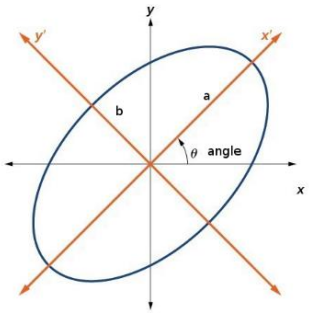


Figure 8: Error ellipse (Source: https://anitagraser.com/)

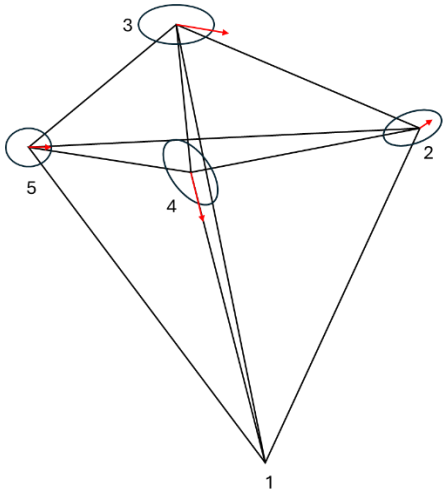


Figure 9: Error ellipses of a 2D network

In cases where the results of the one-dimensional and two-dimensional evaluation are not in agreement, in most cases the results of the two-dimensional evaluation are taken into account.

3D Networks

In the same fashion the deformation of the 3D networks can be assessed with two methods. The first one is the 1D evaluation. Since the evaluation is performed for three dimensions (x,y,z), the second method is with the error ellipsoidal. In order to construct the ellipsoidal, its three axes need to be computed (σ_{max}, σ_{min}, σ_w). The calculation formulas can be found in the works of (Agatza Balodimou & Panou, 2018; Pantazis, 2020)

1D Evaluation: Again, the deformation vector's magnitude is compared with the product of the value of the major semi-axis and the distribution factor for the corresponding level of confidence.

$$|R_i| > c \cdot \sigma_{max}$$

3D Evaluation: A similar procedure as the one presented for the 2D networks is employed. The three ellipsoidal axes (a,b,c in Figure 10) are computed and then augmented by a scaling

factor λ. The deformation vector is then plotted. If the vector is exceeding the limits of the ellipsoidal (dr in Figure 10), then there is strong statistical evidence that a deformation occurred.

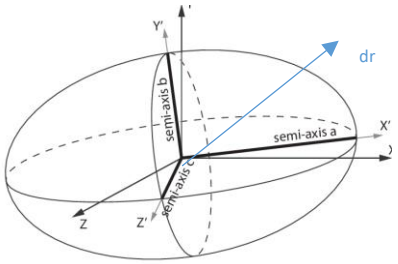


Figure 10: Error ellipsoidal (Source: Ribbens,2015)

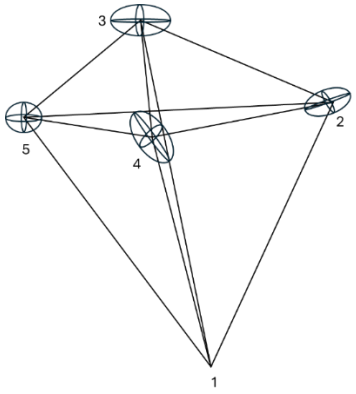


Figure 11: Error ellipsoidals of a 3D network

3.2.3.3.4 Precision

There are three types of errors which affect the measurements (Lambrou & Pantazis, 2011; Agatza Balodimou & Panou, 2018):

- Gross errors: Gross errors display high value. Main source of these errors is the person carrying out the measurement. Their detection is easy, and they can be removed from the computational process
- Systematic errors: The definition of systematic errors has been provided in chapter 2. Systematic errors are expressed with the appropriate mathematical framework and thus can be eliminated
- Random errors: Measurements are inherent with random errors, which can be modelled with stochastic models

The precision of monitoring networks is affected by errors. Uncertainties estimated by the least squares method are related to random errors and the remaining quantity of systematic errors. Furthermore, the stochastic model contains the weights of the measurements, which are related to the nominal accuracy of the measurements. Consequently, the precision is affected by the instrument selected (Table 6) and the methods of executing the measurements, while environmental conditions also affect measurement's quality. Precision of modern instruments and especially those used for monitoring applications is very high. Thus, static 1D and 2D networks are characterized by high precision equal to few mm. For 3D

networks precision is additionally related to satellite geometry and instrument placement, which may lead to multipath phenomena decreasing measurement's precision.

Table 6:Specification of geodetic instruments

	Angle Acc	Distance Acc
Total Station Leica Nova TS60	±1.5cc	With prism: ±0.6mm + ±1ppm Reflectorless: ±2mm + ±2ppm
		Height Acc
Digital level Leica LS10	Invar staff: ±0.3mm Standard staff: ±1.0mm	

3.2.4 Dynamic networks

Geodetic monitoring networks, which are able to provide almost continuous data, are broadly known as kinematic monitoring networks. However, in order to have a unified frame of definitions these networks are defined in this thesis as dynamic.

3.2.4.1 Instruments

Instruments utilized for the dynamic networks are mostly receivers of the GNSS system and total stations. Total stations utilized for kinematic applications are robotic total stations, with the ability to automatically lock and follow the target. GNSS receivers constitute popular instruments for kinematic applications, due to the existence of the Real Time Kinematic method.

3.2.4.2 Results

Results of the continuous monitoring are time-series of coordinates of the network's points (Alevizakou, 2017). By analyzing the time series, properties of the structure's vibration can be defined. Furthermore, the estimation of velocity and acceleration are important parameters as they reflect the evolution of deformations (Bayrak & Yalçınkaya, 2003)

Even though the computational basis is still estimating coordinates of the network's points, the computational procedure is not the same. As mentioned above dynamic networks differ also in the adjustment type (Pikridas , et al., 2009). Furthermore, additional algorithms are utilized such as Kalman filter. It is worth mentioning that kinematic properties are calculated with polynomial or harmonical functions (Alevizakou, 2017). Two main approaches adopted for kinematic networks are (Bayrak & Yalçınkaya, 2003):

Linear models

$$x_i^{t_n} = v_i(t_n - t_0) + x_i^{t_0} = v_i \cdot \Delta_t + x_i^{t_0}$$

Where,

- $x_i^{t_n}$: point position at time t_n

- $x_i^{t_0}$: point position at reference time t_0
- v_i: point's velocity

Polynomial functions

$$x_i^{t_n} = \frac{dx}{dt}(t_n - t_0) + \frac{1}{2}\frac{d^2x}{dt^2}(t_n - t_0)^2 + x_i^{t_0} = v_i \cdot \Delta_t + \frac{1}{2}a_i{\Delta_t}^2 + x_i^{t_0}$$

Where,

- $x_i^{t_n}$: point position at time t_n
- $x_i^{t_0}$: point position at reference time t_0
- v_i: point's velocity
- a_i: point's acceleration

For polynomial models, Kalman filter can be utilized for the adjustment (Bayrak & Yalçınkaya, 2003). Trigonometric models are utilized when measurements are obtained from satellite methods, due to the existence of pseudo-signals (Alevizakou, 2017). Statistical evaluation of the data still takes place as described in the above chapter.

A table displaying advantages and disadvantages of the two traditional methods follows.

	Advantages	Disadvantages
Geodetic	High precision (a few mm on average)	More difficult to be fully automated
	Estimation of both absolute and relative measurements	Visibility and accessibility issues
	Measurements defined in selected reference system. Correlation with causative phenomena can be achieved	Affected by weather and lighting conditions
	Global monitoring	Less frequently used for capturing dynamic responses
	Non destructive	Human in the loop procedures
	Estimation of measurement errors to assess the reliability of solution	More expensive (time and cost)
		Instrument calibration and tests associated with their right function are required
Geotechnical	Localization of damage	Calibration required
	Appropriate for capturing dynamic responses	Relative information provided
	Easier to be automated	Affected by site conditions
	Direct information regarding structures properties	Embedded in the structure and after a deformation limit sensors features are also deformed
	Less performance tests required	Additional information is required to assess data quality
	Suitable for continuous monitoring	

4. Fundamental concepts of monitoring systems

4.1 Historical overview

The first form of monitoring was the performance of qualitative, intuitional tests. These tests though effective have limitations due to their nature, i.e. qualitative and based on human perception. Thus, an advanced method for damage detection was advanced, NDT. NDT is the forerunner of SHM. The popularity of NDT rose around half of the 20th century, because mobile monitoring devices became wider accessible. However, NDT still has serious limitations. Human presence is required both for the measurement performance and for the interpretation of the results and the nature of some of these tests is still qualitative. Furthermore, the scale of the assessment is local, while a temporary shutdown of the structure is sometimes required for the fulfillment of the testing campaign. These issues became the catalyst for the development of SHM. The fundamental assumption for the elaboration of SHM systems is presented in the following flow chart (Figure 12) (Farrar, et al., 2024).

Figure 12: Core principle of SHM development

Initially, straightforward modelling was performed. Measurements of the structure's dynamic response were captured and then utilized for simulation execution and damage assessment via FEM. The model was appropriately created based on the geometric and material properties of the structure. Bottlenecks of forward modelling are the following: (i) initial defects, e.g. material defects, are not considered and the same applies for load variations (ii) limitations of computer power (iii) simulations require a great amount of money and time. Solution to some of these challenges was the inverse modelling. Monitoring data of the undamaged state was obtained to update a FEM model to reflect the properties of the undamaged state. Data obtained on a later state, after the occurrence of possible damage incidents, is utilized to update the model. Comparing the two models is the basis for damage detection. However, some challenges persist such as the great amount of time required for this application and the fact that variations are difficult to be considered. Additionally, the system is considered linear and damage has to be extensive to be reliably detected. Due to the limitations of the model-based procedure, the SHM is approached through a data – based procedure and more specifically as statistical pattern recognition problem. SPRP is presented in more detail in the next chapter. For the successful outcome of this approach, training algorithms play a major role. Two types of algorithms can be utilized, namely supervised and unsupervised algorithms. Key difference is that supervised algorithms require data from the damaged state. However, obtaining data from the damaged state is difficult and existing data is scarce. This problem leads to the future approach for SHM and this is the population –

based SHM. Taking advantage of the so-called Transfer Learning, data from similar structures can be utilized for the classification of the structure of interest. However, a matter of attention is that if not sufficient similarity exists then the results are completely unreliable (Farrar, et al., 2024).

4.2 SHM Stages

In literature various categorizations can be found regarding the stages of SHM. However, the key-core stages are the following:

- Data acquisition
- Data processing
- Data assessment
- Decision – making

It is noted that in more mature SHM systems, the last step has also prognostic characteristics. For completeness the above steps are analyzed.

Farrar & Worden (2007) present a four-step process. Process starts with the *operational evaluation* which is the step of investigating the benefit of the investment, defining site properties, defining damage for the structure and restrictions. *Data acquisition, normalization and cleansing* follow. Since data acquisition is not possible without instruments, instrumentation plan is considered part of this step. This part includes the pre-processing in order to minimize variability, exclude potential outliers and ensure the best quality possible of data. Third step is *feature extraction and information condensation*. During this step appropriate quantities are estimated in order to facilitate the damage detection procedure. Damage detection takes place at the fourth step called *statistical model development*, by utilizing appropriate algorithms. Damage detection process is analyzed below.

A similar approach with slight changes is presented by Wang & Ke (2024), who also created a four-step procedure including *pre-assessment*, *data processing*, *damage evaluation and damage diagnosis* and *prognosis and decision-making*. The first two steps correspond to the steps presented by Farrar & Worden (2007). The difference between the two approaches is in steps 3 and 4. Wang & Ke (2024) distinguished the two steps as diagnostic and prognostic. More specifically during step 3, estimation of parameters of interest takes place as well as the damage detection process, making this step diagnostic. Afterwards, during step 4 the RUL is estimated and decision-making regarding repair actions takes place, making this step prognostic.

Chen & Ni (2018) present a four-step procedure for bridge SHM, focusing on managerial aspects of the system. The four-step procedure contains *observation, evaluation, ranking* and *management*. Observation is related to measurements from acquisition up to logging. During evaluation the structure's state is estimated both under usual operating conditions and under emergency conditions. During ranking the results obtained from the previous step are exploited for optimal resources allocation and schedule updating. Last step is management,

which is related to data management. Raw data and extracted features are appropriately stored and methods for quick retrieval are established.

Technical Chamber of Greece described through technical guidelines (Lekidis , et al., 2009) a six-step procedure. The six steps presented are a combination of the steps already mentioned. Namely these steps are:

- Data acquisition: As mentioned above this step includes the instrumentation plan. Apart from that during this step decision regarding the frequency of recording and excitation thresholds for measurement recording are discussed. Data collection and transfer from the instrument to the recording unit are included as well.
- Data transfer: This step includes the transfer of the recorded observations to the processing location.
- Data processing: This step includes all processing aiming at removing outliers, reducing uncertainty and normalizing.
- Data storage: Processed data are then stored appropriately
- Diagnosis: This step includes feature extraction and damage detection
- Data retrieval: Finally, information produced from past measuring campaigns should be easily retrieved for future assessment

An even more detailed procedure is established including additionally risk assessment analysis by Inaudi (2009).

Based on all of the above, for SHM process integral parts are:

- Instruments and recording units
- Data transfer network
- Processing algorithms
- Damage detection algorithms and models

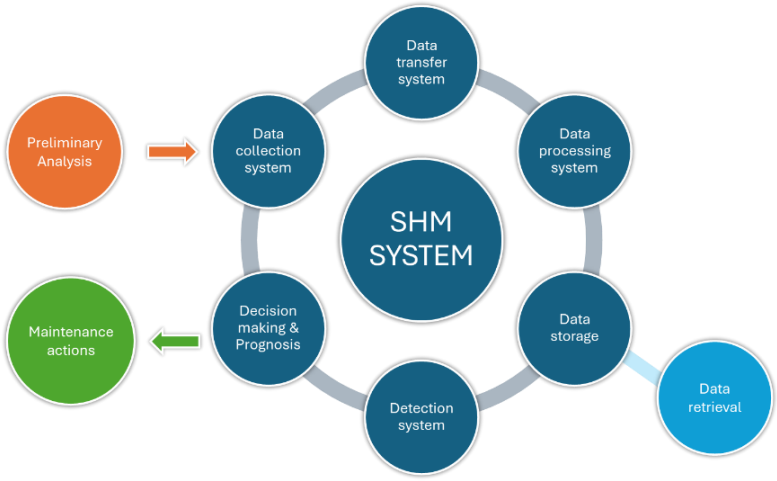


Figure 13: SHM system overview

Combining the steps presented by the various authors, a comprehensive SHM system is similar to the one presented in the above figure (Figure 13). It is noted that for in-situ, real-

time applications some of these steps are not applicable. However, since not all currently established operating systems cover modern system's requirements, all the steps are included.

4.3 Damage detection

One of the major components affecting system's design is the level of damage that the system will be able to detect. Mostly, a four-level damage detection classification is identified (Lekidis , et al., 2009; Gharehbaghi, et al., 2021).

- Level 1: The system has the ability to detect the existence of damage
- Level 2: The system has the ability to detect the existence and the location of damage
- Level 3: The system has the ability to detect the existence, the location, the type and severity of damage
- Level 4: The system apart from the above capabilities has predictive capabilities regarding the estimation of the remaining useful life of the structure

This four-step analysis can be further detailed as suggested by other researchers (Farrar & Worden, 2007; Chen & Ni, 2018). More specifically Level 3 can be divided into two separate levels, with the first one being able to detect the type of damage and the second the severity. It is evident that the higher the level of damage detection, the more information provided and the more complicated the system is.

4.4 Classification of SHM systems

Various SHM systems, tailored to specific structures, are produced by combining different parameters. Inaudi (2009) presented the following classification categories (Figure 14).

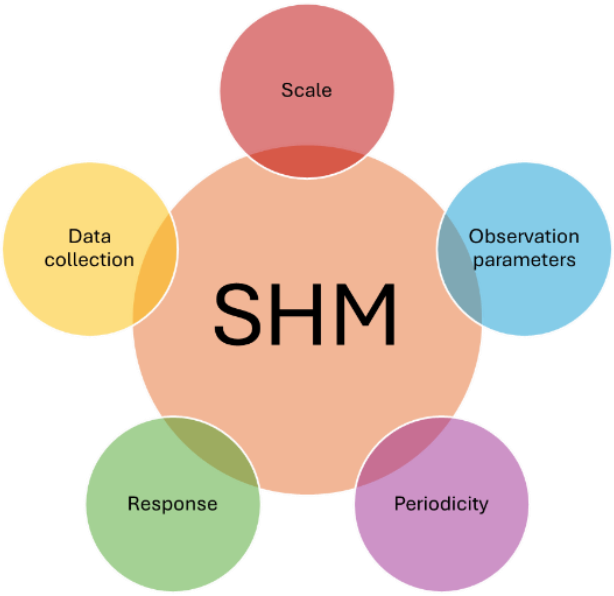


Figure 14: Classification categories based on (Inaudi, 2009)

A more elaborate classification is presented by Gharehbaghi, et al. (2021) (Figure 15).

Figure 15: Classification categories from (Gharehbaghi, et al., 2021)

4.4.1 Scale

Scale represents the spatial coverage of the monitoring system. The most common types are local and global (Glisic & Inaudi, 2003; Chen & Ni, 2018; Gharehbaghi, et al., 2021). Where local damage detection is performed for specific parts of the structure while global investigates the state of structure as a whole. Inaudi (2009) mentions 4 scale levels starting from (i) local monitoring, applied to specific parts of the structures and focusing on the material condition, proceeding with (ii) member level which includes investigating the state of structure's specific members and (iii) global level which investigates the whole structure's state and finishes with (iv) network level which includes monitoring structures constituting parts of a greater project.

4.4.2 Response

As mentioned in chapter 3, monitoring systems can be either static or dynamic (Glisic & Inaudi, 2003; Inaudi, 2009; Gharehbaghi, et al., 2021). Static responses are associated with slowly alternating phenomena, while dynamic responses are associated with dynamic parameters, such as acceleration.

4.4.3 Computation

This category is associated with the models utilized for damage detection. Mainly two computational methods are utilized, namely model-based and signal-based approaches (Gharehbaghi, et al., 2021; Farrar, et al., 2024). Model based approaches utilize a physical model of the structure and by using measured data perform various deformation simulations.

Signal-based approaches are statistical problems utilizing classification algorithms for damage detection (Figure 16).

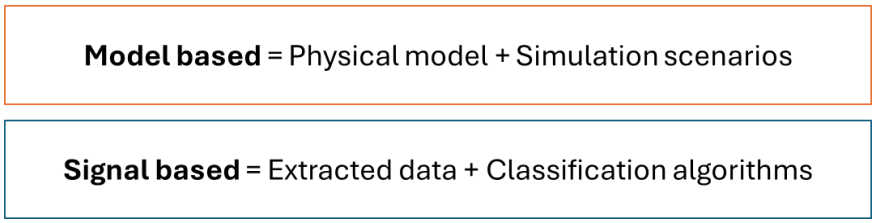


Figure 16: Difference between model-based and signal-based approach

4.4.4 Periodicity

Periodicity refers to the time interval between two consecutive measurements. When measurements are performed at wide time intervals, then measurements are characterized as periodic. When the system is set to record measurements in an automated way and at smaller time intervals it is considered semi-continuous. Finally, a system which is automatically performing continuous measurements is characterized as continuous (Inaudi, 2009).

4.4.5 Feedback

Feedback can be either active or passive. Active feedback is the result of a deliberate signal transmission. Passive feedback refers to observations captured by permanently installed sensors, which at predefined intervals capture the values of the parameters of interest. (Gharehbaghi, et al., 2021).

4.4.6 Excitation

Excitation can be either forced or ambient. Ambient excitation refers to vibration caused by external factors and has a probabilistic nature. Forced excitation refers to deliberately introduced vibration. Forced excitation must be conducted in a controlled manner. (Gharehbaghi, et al., 2021)

4.4.7 Parameters

Parameters refer to the type of measurements the system is designed to record. Parameters are mechanical, chemical, physical, environmental, actions etc. (Inaudi, 2009). Combination of different parameters is a common monitoring practice.

It is evident that there is a great number of possible SHM systems due to the large number of parameter combinations. Based on the definition provided by Farrar, et al. (2024), a modern SHM system is the following combination:

- Scale: Global
- Periodicity: Semi- continuous / Continuous
- Computation: Signal-based
- Response: Dynamic

4.5 Challenges

Despite the rich literature regarding technical aspects of SHM and the undeniable qualitative benefits of these systems, associated with enhanced safety and reduced uncertainty, these systems are not widely adopted as a tool for decision making which drives maintenance procedure and actions. Various reasons obscuring broader adoption exist, both technical and managerial. From a managerial perspective the main reasons obscuring their implementation are:

- High cost: The implementation of such systems entails a great amount of costs (Kamariotis, et al., 2022). More specifically there are direct costs related to purchase, installation, operation, maintenance and replacement of the systems and indirect costs associated with training personnel, software purchase etc. Additionally, the vulnerability of the sensors, which is a technical challenge, poses also a managerial challenge due to the increased replacement costs
- False indications: False indications, i.e. false alarm or false silence, do appear as technical challenges. However, owners' knowledge of this defect increases the reluctance of adopting these solutions as it may lead to unnecessary costs.
- Lack of knowledge of potential benefits: Not all stakeholders are familiar with the operation and results of an SHM system and consequently with the potential benefits these systems provide. Solution to this issue could be a method for quantifying the benefits of these systems and translating their value into monetary units (Kamariotis, et al., 2024).
- Heterogeneous stakeholders: Apart from the fact that not all stakeholders are familiar with the systems, not all stakeholders are also interested in the potential benefits. The heterogeneity of the stakeholders may result in limited interest regarding the maintenance (Farrar & Worden, 2007).
- Lack of standardization: Existence of frameworks referring in detail to the implementation of SHM during operational phase could be considered as a factor facilitating their wider adoption. However, the non-binding nature of the framework and lack of standardization regarding processes and procedures of these systems, i.e. computational methods, thresholds definition, etc., is a challenge which obscures wider adoption (Del Grosso, 2014).
- Lack of real-world practical applications: The great number of publications regarding SHM systems, their technical aspects and application is not analogous to the number of real-world practical applications in infrastructure projects (Kamariotis, et al., 2022).

Apart from these major managerial challenges, there are also technical and computational challenges, which need to be taken into consideration. Table 7 contains some of these challenges.

Table 7: Technical and computational challenges

Type	Description	Reference
Technical	The adverse operational conditions of the sensors may cause functional issues and hence lead to unreliable data	(Giordano, et al., 2022)
	The instrumentation of the structure with various types of sensors, whose data transfer time differs, results in increased demand for autonomy and "network traffic"	(Zhang, et al., 2024)
	Technologically advanced sensors produce larger amount data resulting in increased demand for storage area	
	Measurement uncertainties	
Computational	Data-driven models may produce unreliable results if the training data is not sufficient	(Farrar, et al., 2024)
	The utilization of various type of sensors which produce differing results requires the adoption of complex algorithms in order to process and transform data	(Zhang, et al., 2024)
	Uncertainties are inherent in measurements. Some observations may be outliers and degrade the quality of the system's result. The adoption of appropriate algorithms, which exclude the outliers without affecting negatively the final result poses a computational challenge	(Zhang, et al., 2024)

5. New – age technologies

Potential solutions to some of the aforementioned challenges could be the technologies of Construction 4.0. Construction 4.0 is a relatively new concept and stems from the Industry 4.0 concept.

5.1 Definitions

The first use of the term is a matter of debate in literature. El Jazzar, et al., (2021) provide a short historical review mentioning the first appearances of the idea of Construction 4.0, with the very first appearance dating back to 2014 in the work of Lasi et al.(2014). Siriwardhana & Moehler (2023) mention that the term was first adopted by Li and Shi (2015) in their work related to Construction 4.0 for dam projects (Li & Shi, 2015). Other researchers (Forcael, et al., 2020; Van den Heijden, 2023) state that the term was first adopted by the German company Roland Berger GMBH in their report for the digitization in the construction sector (Berger, 2016). Forcael, et al. (2020) provide a more detailed overview regarding this issue, clarifying the difference in context of the three works claiming to be the first introducing the term. In the work of Lasi et al (2014), the key terms Industry 4.0 and construction appear together for the first time. Li and Shi (2015) use the exact term, Construction 4.0, but exclusively for construction of dams. Gerber company in 2016 presents the term Construction 4.0 as a broader idea aiming at transforming the construction sector in general.

An official definition for the term has not been provided, resulting in various definitions with slight differences. Definitions existing in literature are included in Table 8**.** The table includes the attempt of the authors to describe the concept of Construction 4.0. According to Siriwardhana & Moehler (2023), definition differences appear also among countries, reflecting distinctive demands and status of the construction sector in each country. Despite the lack of a uniform definition, the fundamental principles are ubiquitous: digitalization, interconnectivity, new technologies.

Table 8: Definitions of Construction 4.0 found in literature

Definition	Reference
"Digitalization of the physical ecosystem followed by its virtual management"	(Balasubramanian, et al., 2021)
"Digitalization of the construction industry and industrialization of the construction processes"	(Forcael, et al., 2020)
"Digitization and industrialization of the industry that 1) enable real-time, horizontal, and vertical integration and connectivity of stakeholders across the construction project lifecycle, 2) promote the advancement of construction processes by employing mechanization and automation, and 3) bridge the gap between the physical and cyber environments"	(El Jazzar, et al., 2021)

"Construction 4.0 combines Cyber-Physical Systems and Digital Ecosystem to create a new paradigm for the design and construction of our built environment assets"	(Sawhney, et al., 2020)
"An innovative construction management technique, driven by Industry 4.0 technologies, that allows for the creation of a smart construction site"	
"A combination of cyber-physical technologies that supports a smart construction site, digital modeling (Building Information Modeling (BIM); digital twin – a digital replica of potential and actual physical assets, processes, people, places, systems, and devices), simulation, and virtualization"	(Prieto, 2021)

5.2 Technologies

It is evident that technologies play a major role in the implementation of Construction 4.0. The various technologies falling under the umbrella of construction 4.0 are utilized throughout the lifecycle of a project. El Jazzar, et al. (2021) presented the potential of utilizing 9 of the major technologies of Construction 4.0 per construction phase (Figure 17).

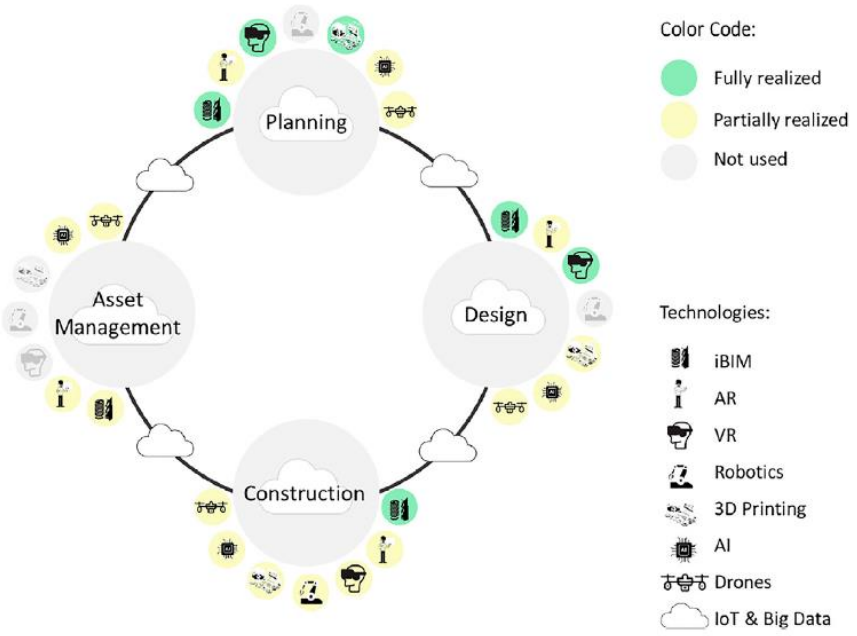


Figure 17: Construction 4.0 technologies and their utilization per construction phase (El Jazzar, et al., 2021)

According to European Commission (2021) technologies appertain to certain categories: data acquisition, digital analysis and automation (Figure 18). It is noted that materials with advanced properties can be considered as a fourth category, but they are out of scope of the present thesis.

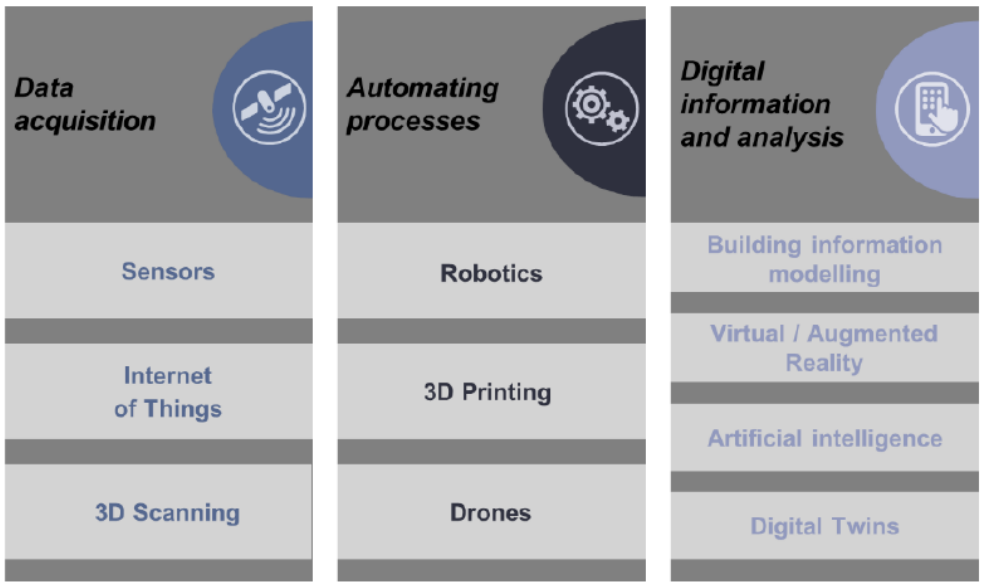


Figure 18:Categories and technologies of Construction 4.0 (European Commission, 2021)

5.2.1 Building Information Modeling

According to BIM handbook (2008) "*BIM is a modeling technology and associated set of processes to produce, communicate, and analyze building models".* National BIM Standards of United States mention that BIM is a digital depiction of structure's properties, both physical and functional, and hence it operates as shared knowledge reservoir and a decision-making tool throughout the lifecycle of a project. Gao & Pishdad-Bozorgi, (2019) describe BIM as a process enhancing all project's phases by utilizing information produced throughout the structure's lifecycle. Despite the diverging definitions, BIM includes a model of the structure, information and serves as a shared means of communication between the stakeholders providing clarity and enhanced interpretation.

According to the information the model includes, the dimension of the BIM is defined. The simplest form is the 3D BIM containing geometric and geographic information. 4D BIM additionally contains time information. 5D BIM additionally contains information about costs. 6D contains information about sustainability and energy efficiency. 7D BIM contains information about facility management. The above dimensions are considered as the standard dimensions of BIM (Van den Heijden, 2023). In Figure 19, BIM dimensions according to the information included in the model are presented.

BIM is considered fundamental technology for Construction 4.0, facilitating the operation of other Construction 4.0 technologies (Van den Heijden, 2023). It is worth noting that BIM has been tested as a concept before the appearance of Construction 4.0. Its broad acceptance as construction improving technology is considered to contribute to faster adoption of Construction 4.0 idea.

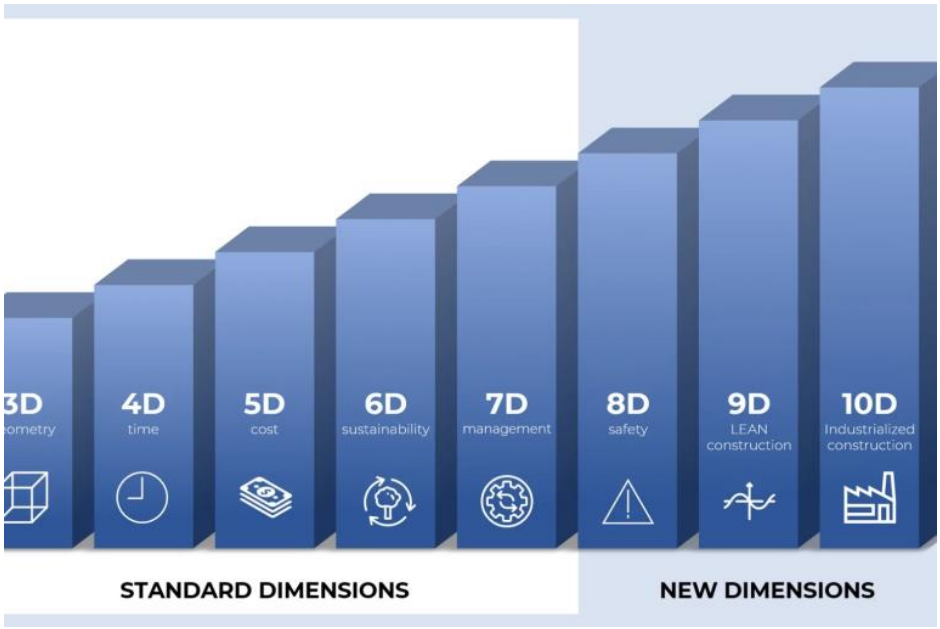


Figure 19: BIM dimensions https://www.harmony-at.com)

Combining the data acquired from the system's sensors with a BIM model, provides an advanced tool for interpretation and analysis enhancing collaboration and understanding (Gragnaniello, et al., 2024).

5.2.2 Digital Twins

Digital twins are a relatively new technological concept, for which a uniformly accepted definition hasn't been adopted. In fact, the definition varies depending on the field and purpose of application (Krouskos, 2024). Technological company IBM offers a short and simple definition of the term (IBM, 2021). The definition is the following: "*A digital twin is a virtual representation of a physical object or system designed to reflect the physical object accurately*". IBM (2021) also states that digital twins are updated with real-time data received from various sources and by utilizing other technologies, i.e. artificial intelligence etc., they provide a basis for informed decision making.

The idea of using a "twin" as a tool for improved management of a physical object is not a new concept. This idea dates to the 60s when NASA was creating physical twins of spacecrafts (Figure 20). Simulations were executed on the twin and the insights of the simulations were the basis of decisions regarding the departed spacecrafts (IBM, 2021; Krouskos, 2024).

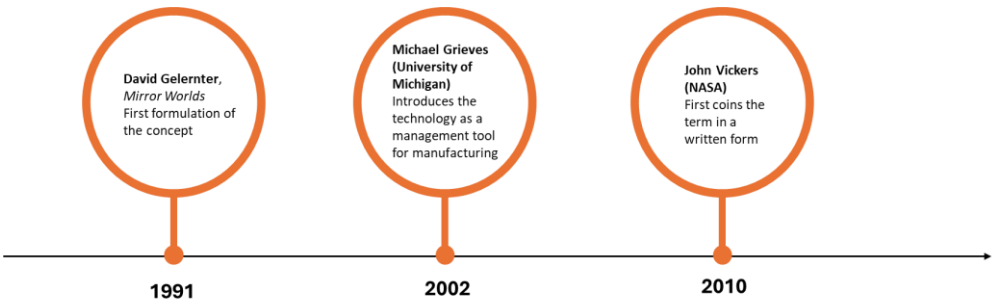


Figure 20 : Digital twins key milestones

The function of digital twins is based on other technologies of Construction 4.0. BIM is the keystone of Digital Twins. BIM provides all the information regarding the design and construction of the structure and constitutes digital representation. IoT is a required technology as well. During operational phase, the interconnected devices of IoT offer real time data, regarding the structure's behavior. The data provided by IoT is combined with the BIM model creating a digital version of the physical structure and thus allowing damage simulation for different damage scenarios (Tjahjadi, et al., 2025).

5.2.3 Internet of Things

IoT is a set of physical devices (things) interconnected with the internet. These devices have the ability to collect and share data in real-time. According to the definition, IoT connects the physical ecosystem with the cyber ecosystem (Pantouvakis, 2024). A general representation of how IoT works is given below:

The devices of the IoT network can be general devices and sensing devices which record specific parameters. These separate general devices connect to the network with the help of a gateway, while gateway also processes the data captured by the sensing devices and transmits them to the network (Gillis & Yasar, 2025).

The sensors at a construction site can be installed on:

- The structure and measure physical properties.
- Machinery and record parameters such as position, speed and performance.
- Personnel in the form of smart wearables, and record health related parameters such as pulses, blood pressure, oxygen, body temperature etc.
- And in the wider area of the construction site, and record environmental parameters such as temperature, humidity, wind speed etc.

It is evident that data collected by each sensor varies. A large amount of heterogenous data is collected by sensors, exchanged and processed in real time, to inform managers and facilitate the decision-making procedure and allow remote action.

Sureshkumar & Vennila (2019) state that IoT could be a useful technology for SHM. The sensors measuring the parameters of interest for the condition assessment of the structure produce a large volume of data. The data collected and transferred in real time by the sensors can be stored in a cloud environment, while they can be accessed and evaluated remotely.

5.2.4 Unarmed Vehicles

UAVs are commonly defined as flying agents whose piloting doesn't require human presence as they can be either managed distantly or self-piloted (Hung & Gonzalez, 2012). UAVs with incorporated sensors can be a helpful solution for construction activities, for which human presence is considered either unsafe or costly (Saleem , et al., 2015).

UAVs can be considered as data acquisition technology, when appropriate equipment is attached to them. Cameras and laser sensors are common examples of such equipment. Examples of laser sensors are Lidar sensors and Laser Scanners.

5.2.5 Artificial Intelligence & Machine Learning

AI is the field of computer science associated with machines simulating human intelligence, when performing practical tasks (Alevizakou, 2012; Pantouvakis, 2024).

ML is a subfield of AI and it is associated with the aspect of learning from experience. By employing algorithms ML systems both learn and upgrade their results (Helm, et al., 2020).

Artificial Neural networks are part of Computational Intelligence and hence they are analyzed in this chapter. For the sake of simplicity, the reference to Neural Networks is equivalent to Artificial Neural Networks. As their name suggests, neural networks attempt to simulate human brain's function in order to solve problems. Another detailed definition is the following: Neural networks are networks simulating human brain's function, which are trained with data to recognize patterns (Alevizakou, 2012; Alevizakou, 2017).

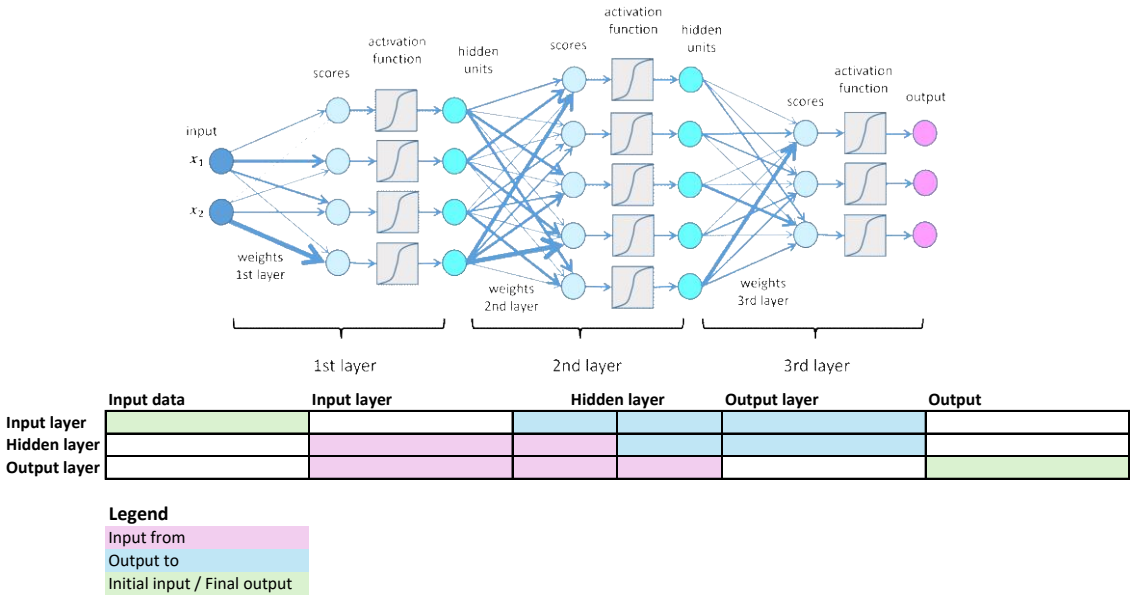


Figure 21: Links between the layers of neural networks

Input data is required for the initiation of the process. The contact point of the input data and the neuron is called synapsis. The input data does not contribute equally to the output generation. The weight of each input data is called synaptic weight. The input data, after being appropriately modified based on its synaptic weight, is summed up. For this procedure a summing junction is utilized. The sum is the output for the activation function, which produces the network's output. The process described above is for a single neuron. Neural networks though contain a set of neurons which are distributed in layers (Figure 21). In any case, neural networks consist of input, hidden and output layers (Alevizakou, 2012).

In the following table a short classification of neural networks is presented.

Table 9: Classification of neural networks

Classification category	Types	Description
Layers	▪Single- layer ▪Multi-layer	Single-layer neural networks contain only the input and output layers, whereas multi-layer networks contain additionally at least one hidden layer
Signal Feedback	▪Feedforward ▪Recurrent	Forward feedback networks transfer the signal to the next layer until reaching the output layer and the network's final output, whereas at recurrent networks a recurrent loop exists, transferring the output signal of a layer as an input either back to a preceding layer or to the same layer
Connection	▪Fully connected ▪Partially connected	In fully connected networks the neurons of a preceding layer are connected with all of the neurons of the next layer (Figure 21), whereas on partially connected networks not all the neurons of the preceding layer are connected to all the neurons of the next layer

The large set of data produced by modern sensors can be analyzed through algorithms of AI and ML. Furthermore, neural networks offer a great tool for predictions enhancing the capabilities of monitoring systems for predictive maintenance.

5.3 Application of technologies in SHM

The applications of technologies in SHM are from the proceedings of the 5th Joint International Symposium on Deformation Monitoring, which took place in Valencia, in 2022.

Ding, et al. (2025) utilized digital twin technology for monitoring Danjiankou dam, located in China, and provided a respective framework. Integral parts of the framework are the physical model of the dam, monitoring observations and Bayesian updating. The last part is analyzed in detail in chapter 6. By combining these parts, a real time simulation is achieved in order to diagnose the state of the dam. Moreover, the system is able to make predictions by utilizing worst case scenarios. Authors mention that by this approach the diagnosis and prognosis are more accurate and overcome challenges of model-based or data-based monitoring.

Tjahjadi, et al. (2025) state that BIM and digital twins provide benefits for maintenance management such as enhanced understanding for stakeholders, more informed use of resources and increased cooperation. In their work, they created a digital twin framework for monitoring a bridge in Pandansari, Indonesia. The framework provided is based on

photogrammetric methods as it constructs digital twin from images, while damage detection is performed by image data as well.

Piniotis & Gikas (2022) utilized deep learning neural networks for damage detection on a model Bailey type bridge. Measurements were carried out using a radar system (ground-based radar interferometer). The method adopted allows automatic feature extraction for the SPRP. The detection results were promising since they were characterized by high accuracy in distinguishing damaged and healthy state. An additional novelty of the approach presented is that the authors exploited the "Transfer Learning" ability of ML since the training data are limited.

Parente, et al. (2022) exploited the possibilities of ML and investigated an automated crack detection method driven by image data. The proposed system minimizes human-in -the-loop and excessive processing which affect data quality. The system is characterized by high autonomy in crack detection. However, the method is not suitable for locations with varying illumination conditions.

Si, et al. (2022) presented the results of a combined approach utilizing UAV and InSar for land deformation monitoring of an airport. More specifically, object of interest is the Ankang Airport located in China. The geological conditions of construction site are adverse, while the terrain of the area was characterized by intense height differences. Thus, a big volume of soil was used for embankment. For the aforementioned reasons, land monitoring of such an important infrastructure project is considered of paramount importance. A DEM of the area is created utilizing the UAV. Then SAR satellite data were exploited for the estimation of deformations. These data are images obtained from Sentinel 1A satellite. The model proposed can minimize human observations and can be used for large-scale projects, i.e. airports. Moreover, the results from the sensor are combined with meteorological data in order to identify causative factors of deformations

Dreier, et al. (2022) explored the potential of combing UAV and laser scanning technology for dam monitoring. To verify the accuracy of the proposed method, authors compared the results with the respective outcomes of terrestrial laser scanning, a high accuracy method already widely used for deformation monitoring. Results, though affected by environmental variations and flight properties, are promising. Thus, this method can be utilized for kinematic applications, large-scale projects and areas with site accessibility issues.

Meng, et al. (2022) explore a SHM system utilizing technologies of Construction 4.0. and they present a case study of the long span Forth Bridge in Scotland. Three core parts characterize this experiment: smart sensors, large volume of data, digital twin and AI for monitoring. Sensors forming the system are accelerometers, GNSS equipment, tiltmeters and instruments dedicated to record meteorological data. Large sets of pre-processed data are uploaded to a respective cloud. Furthermore, they analyze the potential of combining digital twin technology with AI in order to exploit ML properties. With this experiment they explored the use of emerging technologies for efficient data storage and management.

5.4 Challenges

It is expected that the implementation of new technologies is related to certain challenges. Mohd-Rahim, et al. (2022) presented an extensive investigation of risks associated with implementing new technologies in SHM. They classified risks into two main categories endogenous, solely related to technologies, and exogenous. Van den Heijden (2023) also presents some challenges related to Construction 4.0 technologies. Four major issues are the following:

- Security: Since many new technologies utilize cloud and internet services cyber-security issues arise. Among those are privacy, potential cyber-attacks and confidentiality issues (Meng, et al., 2022; Mohd-Rahim, et al., 2022; Van den Heijden, 2023)
- Costs: Implementing new technologies doesn’t come with no cost. On the contrary, great amount of money must be given for hardware and software (Van den Heijden, 2023)
- Technical issues: New sensor technologies are characterized by high complexity and generation of high amount of data. Thus, management of these data poses a challenge (Mohd-Rahim, et al., 2022; Van den Heijden, 2023)
- Skilled personnel: To achieve successful implementation of new technologies appropriately trained personnel is required. However, unwillingness to change is a possible challenge (Mohd-Rahim, et al., 2022; Van den Heijden, 2023)

6. Quantifying the benefits of monitoring systems

As mentioned above, two of the main factors obscuring wider adoption of SHM systems are the lack of awareness regarding the potential benefits of utilizing monitoring systems and the high cost associated with them. The costs related to these systems are (Giordano, et al., 2020; Chadha, et al., 2021):

- Purchase cost
- Installation cost
- Operation costs and costs associated with training the personnel
- Replacement costs, since the lifecycle of the systems is shorter than the lifecycle of the respective project
- Emergency costs in case of damage

The sum of the above costs is considered the investment cost of a monitoring system, and it is certainly not negligible. Despite the undeniable qualitative benefits of these systems, their implementation is considered an investment and thus the owner desires to realize the profit gained from utilizing the information provided by a monitoring system for operational and emergency management.

The framework of VoI is a solution to these two managerial challenges. The idea of VoI is not new. According to Zhang, et al. (2021) VoI appeared approximately around the middle of the 20th century (1950s – 1960s). The need, though, to evaluate numerically the potential benefits of an SHM system is rather recent.

The whole computational procedure roots in Bayesian decision analysis and the maximum utility theorem (Zonta , et al., 2014; Giordano, et al., 2020; Giordano, et al., 2022; Kamariotis, et al., 2022; Kamariotis, et al., 2022; Giordano, et al., 2023; Kamariotis, et al., 2024). The basic idea behind this metric is that owners can opt for the purchase and installation of a monitoring system after they compare monetary values associated with (i) maintenance process without information for the structure's state and (ii) maintenance supported by an SHM system. The potential cost savings are the result of VoI procedure, which constitutes a concrete and tangible basis for decision making. Apart from decisions regarding the adoption of monitoring systems, VoI provides a computational framework for the assessment of different sources of information, different monitoring schemes and for monitoring a monitoring system (Giordano, et al., 2022). A brief analysis of the method's framework is provided.

6.1 Bayes theory

One of the two integral aspects of VoI theory is Bayes theory. According to Bayes theorem if A and B are two contingencies and P(B)>0, the probability P(A|B) equals

$$P(A|B) = P(B|A) \cdot \frac{P(A)}{P(B)}$$

The advantage of Bayes theorem is that it correlates the probability of A|B with the probability of B|A. To compute the probability of A conditional to B, the probability of A is

required. Thus, prior probability for A is required. Prior probability constitutes an estimation based on experience or other knowledge. As soon as more information is available the probabilities are updated, and the posterior probabilities emerge. It is noted that during the update procedure the previous posterior probability is being transformed into prior probability. Consequently, the two main parts of Bayes theory are the prior analysis and the posterior analysis. Instead of considering two contingencies, two continuous random variables are considered a and b. Bayes theorem is now expressed as:

$$f(a|b) = \frac{f(b|a)\, f(a)}{\int f(b|a)\, f(a) da}$$

One more element of Bayesian analysis is that independent variables are considered as random variables (Polymeropoulos, 2015; Meligkotsidou, 2020).

6.2 Maximum utility

Maximum utility theory states that the action which maximizes the expected utility is selected as optimal (University of Ioannina, n.d.; Papadakis, 2022). The fundamental principle of utility theory is:

- If $U(A_1) > \mathrm{U}(A_2)$, action A_1 is preferable than action A_2
- If $U(A_1) = \mathrm{U}(A_2)$, there is no discrete preference between the two actions

6.3 VoI framework for monitoring applications

For engineering activities and specifically for SHM applications, the state of the structure (S) and the information acquired from a monitoring system (R) are considered as random variables, with respective probabilities P(S) and P(R), while the repair measures or actions (A) depend on both structure's condition and (if available) structural information. The probability is updated when data for the structure's state is available. The probability that the structure is in state S_l conditional to the observation Rj is expressed as:

$$P(S_l|R_j) = \frac{P(R_j|S_l) \cdot P(S_l)}{P(R_j)}$$

Where:

- The probability the system produces the result Rj when its state is S_l is the likelihood function. Likelihood function expresses how probable it is to observe R_j when the structure's condition is S_l

The above probability is the one of the posterior analysis. It is evident that the assessment of the investment is carried out before the installation of the sensors and the acquisition of actual data. As a result, when assessing the investment of a monitoring system a pre-posterior analysis is conducted. To summarize, three analyses can be carried out:

- Prior analysis: Only already existing knowledge and experience are utilized to calculate the probability of the structure's state

- Posterior analysis: Actual information about the structure is utilized to calculate the probability of the structure's state
- Pre-posterior analysis: The probability of the structure's state is calculated considering the intention of installing a data acquisition system utilizing estimated values for the potential outcomes of the system

To highlight the benefits of the system for operational and maintenance management, one must compare the results from the pre – posterior analysis with the results from the prior analysis. The hypothesis for the prior analysis is that no knowledge obtained from an SHM system is utilized. The utility function is related to the actions adopted, which in the case of an SHM system are driven by the system's output. The ultimate goal is to maximize the expected utility.

$$\hat{A} = \max_n u(A_n)$$

$$\hat{A}_{R_J} = \max_n u(A_n|R_j)$$

The utility computed by the first equation is based only on the structure's state probability, which as mentioned above is an estimation. The utility computed by the second equation is considering the possible observations of the system. For many engineering applications, utility is considered as negative cost, which is more straightforward. As a result, the equations are transformed into:

$$\hat{A} = \min_n c(A_n)$$

$$\hat{A}_{R_J} = \min_n c(A_n|R_j)$$

The above general framework presented by Giordano, et al. (2023) is representative of the use of VoI for SHM assessment. For SHM applications the term VoI can be transformed into VoSHM, to highlight that the information whose contribution to management is examined is obtained from an SHM system.

To demonstrate the use of this framework a simple numerical example issued by Zonta , et al., (2014) is presented.

6.3.1 Numerical example – Streicker Bridge

Zonta , et al. (2014) utilized the VoI method to assess the benefits of implementing an SHM system on a pedestrian bridge at Princeton University. The selection of this particular bridge was made because the bridge is already instrumented. However, it is important to note that the list of actions to be performed and the bridge's state are estimated and hypothetical.

The application performed is purely for educational purposes and the stage of instrumentation is not as thorough as it should be. Thus, the structure is equipped with fewer sensors, and the properties of symmetry were exploited as well (Figure 22). Furthermore, the authors identified eight damage scenarios which could possibly affect negatively the structure. However, for the sake of simplicity, for the numerical experiment only one damage scenario was taken into consideration and the data from one sensor was utilized. The damage scenario, which is considered the most adverse, is the vehicle collision, while the sensor

examined is the one located on the middle of the main span, where greater deformations are captured.

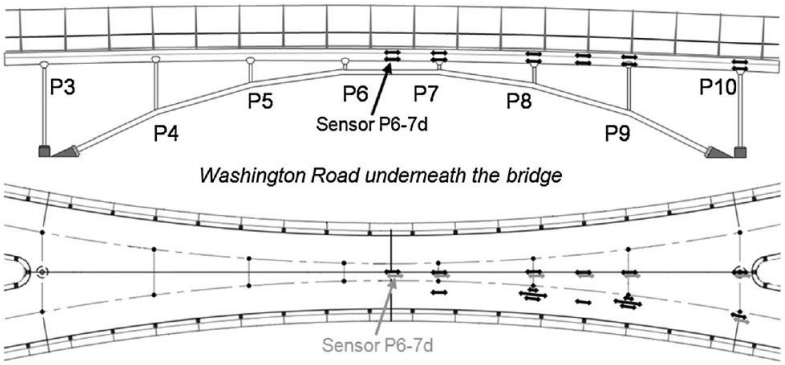


Figure 22: Location of sensors on Streicker bridge. The sensor P6 - 7d is the sensor of interest. (Zonta , et al., 2014)

For the numerical experiment, the authors considered the problem as binary. More specifically:

- The structure's state is either damaged or not damaged with the respective probabilities P(D)=0.3 and P(ND)=0.7. These are the prior probabilities reflecting the manager's estimation based on his/her experience
- The action to be carried out is either close the bridge or do nothing. Moreover, the manager estimates that the closure period is approximately one month.

The costs related to the closure are equal to 4660$ per day. The do-nothing action comes with zero cost if the structure is not damaged. In case the structure is damaged, and the manager decides not to take the appropriate measures, then a cost associated with the injury (I) and fatal incidents (F) is introduced. The cost for injury incidents is equal to 52000$ and the cost for fatal incidents is 3840000$. The conditional probability for these two cases is P(F|D) =0.15 and P(I|D) =0.5. Also, a downtime of two months is required.

Table 10: The binary problem

	Damaged	**Not damaged**
Do nothing	3840000×0.15=576000$ 52000×0.50=26000$ 60×4660=279600$ Total=881600$	0
Close the bridge	30×4660 = 139800$	30*4660 = 139800$

Source: Zonta , et al. (2014)

The sum of the costs related with the do-nothing action when the structure is damaged constitutes the cost of failure C_F, while the cost of closing the bridge is the action cost C_A. The objective is to minimize the costs.

$$C = min(C_{DN}, C_A)$$

The action cost is the same in both structure's states. The do-nothing cost is computed according to the following equation:

$$C_{DN} = C_F \cdot P(D)$$

Based on a-priori probabilities of this example the do-nothing cost is equal to 881600$×0.3=264480$. Consequently, the manager decides to close the bridge since the do-nothing cost is greater than the closure cost.

The above analysis is the prior analysis since no information for the structure's state is exploited. The structure of the example under analysis is equipped with instruments so actual data from the system is available. The next analysis takes into consideration the results of the monitoring system already installed. The monitoring scheme contains observations performed every two years along with visual inspections. The information acquired from the system is values of strain. It is noted that the manager knows the variations due to environmental factors and material properties. The manager considers the following:

- No visual evidence: Negligible strain
- Undamaged state: $\hat{\mu} = 0\mu\varepsilon, \sigma = \pm 300\mu\varepsilon$
- Damaged state: $\hat{\mu} = 1000\mu\varepsilon, \sigma = \pm 600\mu\varepsilon$

The probability density function of the strain equals

$$f(\varepsilon) = f(\varepsilon|D) \cdot P(D) + f(\varepsilon|U) \cdot P(U)$$

The probability density function of the strain is required in order to update the probability of the structure's state according to Bayesian theory. As a result, the probability of the structure being in a damaged state is now expressed as:

$$P(D|\varepsilon) = \frac{P(D) \cdot f(\varepsilon|D)}{f(\varepsilon)}$$

The updated probability is the posterior probability. The cost of closure remains the same as it is not affected by the acquisition of monitoring data. However, the do-nothing cost is now calculated based on the updated probability.

$$C_{DN|\varepsilon} = C_F \cdot P(D|\varepsilon)$$

And consequently, the equation expressing the manager's objective is formulated now as:

$$C' = min\left(C_{DN|\varepsilon}, C_A\right)$$

VoI is the difference of C' and C. Since a probability density function is included in the cost calculation, the result is computed using integral. The authors computed the do-nothing cost, when strain information is utilized, equal to 84600$. The VoI is 55200$ > 0 and the manager is now considering the do-nothing action.

In the same fashion the overall utility of the system can be examined. The implementation of a system is an investment which requires assessment. To proceed with the investment, the manager analyzes the lifecycle costs of the structure with and without the system. The lifecycle costs are considered the sum of initial costs for construction (C_0), cost for regular maintenance (C_M) and cost for repair which is related to exceptional events (C_R). When an SHM system is utilized then these costs are altered. The initial cost is equal to $C_0'=C_0+C_{SHM}$ including also the direct and indirect costs related to the system. Respectively the regular maintenance cost also includes an additional cost for the maintenance of the system $C_M'=C_M+C_{M\text{-}SHM}$ and the cost related to exceptional events is altered and computed based on the example presented above C_R'.

$$VoI = C_{LFC} - C_{LFC}'$$

If:

- VoI > 0 then the implementation of the system is considered beneficial
- VoI < 0 then the contribution of the system is not beneficial

6.3.2 Predefined thresholds

A more elaborate expression of the VoI is presented by Kamariotis, et al. (2022). They considered that the overall cost throughout structure's lifecycle is the sum of costs related to inspections, costs related to maintenance and costs in case of failure.

$$C_{LC} = C_I + C_M + C_F$$

It is noted that costs regarding the design and construction are considered unaffected by the implementation of a SHM system and thus are excluded from the computation of the project's overall costs. The cost in general is conditional to the actions taken and the structure's state. They considered that an action is activated after a predefined threshold (w) is exceeded. Furthermore, the structure's state is expressed through degradation components (θ). Thus, the cost is conditional to w and θ.

$$C_{LC}(w,\theta) = C_A(w) + C_F(w,\theta)$$

Again, in the prior analysis, the degradation components constitute an estimation based on the manager's experience and are expressed through a prior distribution. For the assessment of the system prior to its installation a pre-posterior analysis is carried out. The authors considered vector Z as the history monitoring data. The computational procedure is a bit more complex for the calculation of the total costs utilizing data from a monitoring system. The total cost is expressed with a double integral both for the degradation parameters θ and the monitoring data vector Z.

$$E(C_{total}|w) = \int_{\Omega_\theta}\int_{\Omega_Z} C_{total}(w,\theta,Z) f(\theta,z) dz d\theta$$

For more information regarding the computational procedure followed to define the repair action costs and the cost of failure, as well as the integral the readers are referred to (Kamariotis, et al., 2022)

One more difference is that the pre-posterior case considers the optimized threshold for the activation of a measure. Thus, the total cost is conditional to w' and the VoI is computed respectively.

6.3.2.1 Numerical example

To demonstrate the framework presented, two numerical examples for a two span bridge are included. Degradation components leading to decreased stiffness are examined. The 1st example presented considers scour as the main deteriorating parameter and the 2nd considers corrosion. Since the results of the two numerical examples are analogous, only the 1st example is elaborated. For the definition of the structure's state a simple relationship is considered. For the two different examples, different relationships containing the structure's state condition are defined. The parameters of the two relationships vary. After the computation of stiffness, a FE model is updated to produce monitoring data. Uncertainties are inherent in measurements. Thus, noise is added to the generated data. Synthetic data is generated every year for bridge's operating state. Lastly the degradation components are updated based on the data acquired. Figure 23 displays the prior and pre-posterior distributions. It is noted that the updated distributions tend to reach true values, with this tendency becoming clear after the first 25 years.

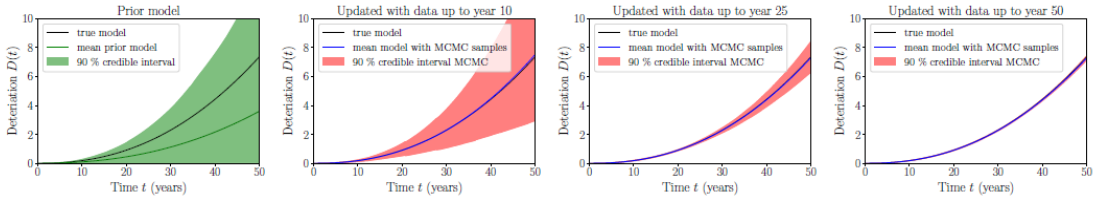


Figure 23: Prior and posterior distributions (Kamariotis, et al., 2022).

As for the costs, the cost of failure C_F is estimated 10^7€ while three different scenarios are adopted for the repair – action cost. Action costs are defined in relation to the C_F. The ratio $C_A/C_F = [10^{-1}, 10^{-2}, 10^{-3}]$. For the computation of the VoI 1000 θ samples were considered. For each sample a series of synthetic data was generated, and 1000 Bayesian updates were carried out.

The results of the numerical example are presented in the figure below:

(a) Life-cycle optimization in the prior case.

$\frac{\hat{c}_R}{\hat{c}_F}$	$w_0^\star$	$\mathrm{E}[C_{\mathrm{tot}}\|w_0^\star]$	t_{repair}
10^{-1}	$\geq 2\times10^{-3}$	45395	no repair
10^{-2}	$\geq 2\times10^{-3}$	45395	no repair
10^{-3}	2×10^{-5}	5924	year 31

(b) Life-cycle optimization in the preposterior case.

$\frac{\hat{c}_R}{\hat{c}_F}$	$w_{mon}^\star$	$\mathrm{E}[C_{\mathrm{tot}}\|w_{mon}^\star]$
10^{-1}	2.1×10^{-2}	12552
10^{-2}	1.2×10^{-3}	3125
10^{-3}	9.9×10^{-5}	1109

(c) Value of information (VoI)

$\frac{\hat{c}_R}{\hat{c}_F}$	VoI (CV)
10^{-1}	32843 (0.34)
10^{-2}	42270 (0.30)
10^{-3}	4815 (0.02)

(d) Value of partial perfect information (VPPI)

$\frac{\hat{c}_R}{\hat{c}_F}$	VPPI (CV)
10^{-1}	35013 (0.23)
10^{-2}	42717 (0.21)
10^{-3}	4918 (0.02)

Figure 24: Results of VoI analysis for the scour example (Kamariotis, et al., 2022).

- Section (a) displays the total costs from the prior analysis
- Section (b) displays the total costs from the pre-posterior analysis, with the optimized thresholds
- Section (c) displays the VoI
- Section (d) displays the value of partial prefect information which is considered the maximum value of VoI.

For all cases VoI is positive, meaning that implementation of a monitoring system is beneficial. It is noted that the most significant savings are realized for the second cost ratio. This is considered rational because it is the most controversial combination. The first ratio results in a small difference between action cost and failure cost. As a result, the manager will decide to do nothing. The third ratio results in a great difference between action cost and failure cost. Thus, the manager will decide to perform the action, with or without the monitoring system feedback.

For an even more elaborate and detailed presentation of the proposed framework the readers are referred to (Kamariotis, et al., 2022). This sequential paper has even more complex and realistic assumptions and realizations, while the computational procedure is the one explained before.

6.3.3 Graphical representation – Influence diagrams

To enhance the use of VoI in a qualitative manner, Straub, et al. (2017) state that influence diagrams constitute a practical interpretation tool enhancing communication and understanding among stakeholders. Figure 25 displays an ID for an SHM system. The diagram, which is a visual representation of the decision-making process, associated with the implementation of a monitoring system, contains nodes and links. The different shapes of nodes represent different aspects of the SHM system. Square nodes depict decisions, circle nodes depict random variables, and rhombus nodes depict consequences of the decisions. The links with the form of arrow aim at revealing causative relations. The fundamental parts of an influence diagram are explained below:

6.3.3.1 Demands

Demand represents everything acting on the structure in the form of loads or degradation components, i.e. environmental aspects, etc. However, the preventive actions taken, affect the demands.

6.3.3.2 Structural condition

The structure's state is affected both by demands and the preventive actions performed. The authors mention that ideally the structure's state should be expressed with physical parameters. However in reality the characterization of the structure's state is done through damage parameters.

6.3.3.3 Structural performance

Structural performance can be expressed as the ability of the structure to be serviceable and operate generating benefit. As it is displayed in Figure 25, structural performance is a function of both the demands and the structural condition.

6.3.3.4 Indicators

Indicators are quantities which the system is designed to observe. Indicators are associated with the demands, the structural condition and the structural performance.

6.3.3.5 Observations

Observations are affected by all the above. Even though this seems irrational, it is compatible with the diagram's logic. The observations reflect the structure's state. Thus, the value of the observations varies according to the state of the structure.

6.3.3.6 SHM strategy – Technologies

This component represents the various combinations of sensors and procedures, computational strategies, etc. which a system can contain.

6.3.3.7 Actions

All the decisions regarding the structure, which can be enhanced by the information acquired from the system. The rhombus is the associated cost. This cost is the SHM system cost, the costs related to the actions which are driven by the SHM information and the risk costs associated with the expected costs in case of failure.

Finally, all the yellow clouds depict the computational methods utilized in order to reach the next node of the diagram.

It is evident that the procedure is more complex, and IDs offer an "easy to understand" way of modelling the decision-making process. The result of the ID allows the computation of the VoI which as mentioned is the difference between the utility of the actions driven by SHM information and the utility of the actions taken without SHM information.

For a binary numerical example, the reader is referred to (Straub, et al., 2017)

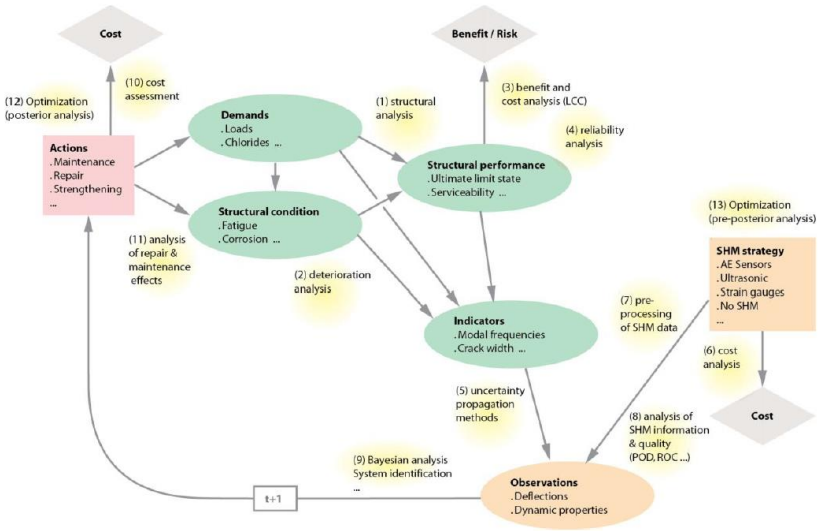


Figure 25: Influence diagram (Straub, et al., 2017)

6.4 VoI for emergency management

To highlight the significance and contribution of SHM systems to emergency management, the method of VoI has been applied and the result is the Value of Seismic Structural Health Monitoring (VoS^{2}HM). The aim of VoS^{2}HM initially was to assist bridge managers with the decisions regarding traffic management after and during seismic event (Giordano, et al., 2023).

The computational procedure, along with the assumptions and realizations are more complex. However, the principles remain the same. The structure's possible damage states, after a seismic event, are expressed as DS_l. Structure's manager has at his/her disposal a list of potential mitigation measures. The cost of each action is conditional to the damage state. Nonetheless, the seismic event (mainshock) is characterized by its magnitude M_m, the epicentral distance R_m and the intensity I_m. The intensity is considered a function of the magnitude and the epicentral distance. Furthermore, it is considered that the structure's state after the seismic event is conditional to the earthquake's intensity. Thus, cost is conditional to magnitude, epicentral distance and structure's condition (Giordano, et al., 2023).

$$E(C(A_n|M_m, R_m, DS_l) = c_F(A_n)(P(F|M_m, R_m, DS_l)) + \bar{c_F}(A_n)(1 - P(F|M_m, R_m, DS_l)$$

The previous examples considered that after the implementation of an action, the risk of failure is minimized. However, for the seismic applications the risk of failure remains after the implementation of mitigation measures, due to aftershocks (Giordano & Limongelli, 2020)

For the pre-posterior analysis the above equation is transformed considering the observations (O) from the system.

$$E(C(A_n|O_i, M_m, R_m, DS_l)$$

Finally, VoI is a triple integral since the VoI is conditional to the characteristics of the seismic event.

To assess the lifecycle benefits of SHM regarding its contribution to emergency management, VoI_{LC} is calculated. Assumptions required for the computation are (i) λ which represents the frequency of seismic events per year and (ii) r which is the discount rate (Giordano & Limongelli, 2020). It is noted that for all the applications resulting in life cycle quantities, appropriate calculations with discount rates are required. The acquisition of SHM data does not come with no cost. The C_{SHM} is the sum of the cost for the initial investment including the installation and an annual cost for the repair and maintenance of the SHM system. Consequently, the net value of the system is the difference between the economic savings expressed through the lifecycle VoI and the lifecycle cost of the SHM system (Giordano & Limongelli, 2020). The main steps for the estimation of VoS^{2}HM are the following:

- Manager defines the potential damage states (DS_l) of the structure (after the seismic event) and the mitigation measures (A_n)
- Probability density functions are selected for the characteristics of the earthquake. It is noted that the intensity is a function of both the magnitude and the epicentral distance as well

- Prior analysis is carried out and the cost for each mitigation action is computed. Actions associated with the minimum cost are considered the optimal solution obtained from the prior analysis
- A likelihood function is established for pre-posterior analysis which is then carried out. Cost for each mitigation measure is recalculated based on the updated probabilities and the action associated with the minimum cost is selected as the optimal solution of pre-posterior analysis
- Computation of VoI is performed. VoI is the difference between the expected costs of the optimum actions from prior and pre-posterior analysis
- The lifecycle VoI is estimated

6.4.1 Numerical demonstration

A simple numerical example by (Giordano, et al., 2023) is provided to demonstrate the use of the VoI for management after seismic events. Subject of study is a 12 floor building. Again, the example has binary decisions. The possible actions are either evacuate or not.

Table 11: Estimated costs

Cost of failure	2000000$ / person	20 people / floor	*480000000$*
Cost of evacuation	1000$ / day / floor	Duration of 60 days	*720000$*

Three different scenarios are examined:

- The prior analysis utilizes sufficient and reliable data and the optimal action minimizing expected cost is selected
- Restricted information is available for the prior analysis but again the optimal action minimizing expected cost is selected
- Manager decides to ignore the prior data as unreliable and to evacuate the building

The results of this experiment reveal a challenge of the method. Actions are conditional to magnitude and epicentral distance. The combination of these two parameters and the optimal action is depicted in implementation. For the 1st scenario the values of VoI are relatively low. The VoI of the 2nd scenario reaches higher values. The same applies to the 3rd scenario. For scenarios 1 and 2 the greatest values of VoI can be detected for combinations of magnitude and epicentral distance resulting in ambiguous action. For the 3rd scenario, the VoI is increased up to the combination of magnitude and epicentral distance, which indicates that evacuation is the optimal solution. It is therefore evident that the results of the method are not so significant if the prior knowledge is sufficient and reliable, since optimized actions are adopted during the prior analysis. However, when the prior knowledge is not reliable the VoI is a powerful tool for management and cost saving, since the high failure costs compared to the evacuation cost compel the manager to stop the operation of the structure.

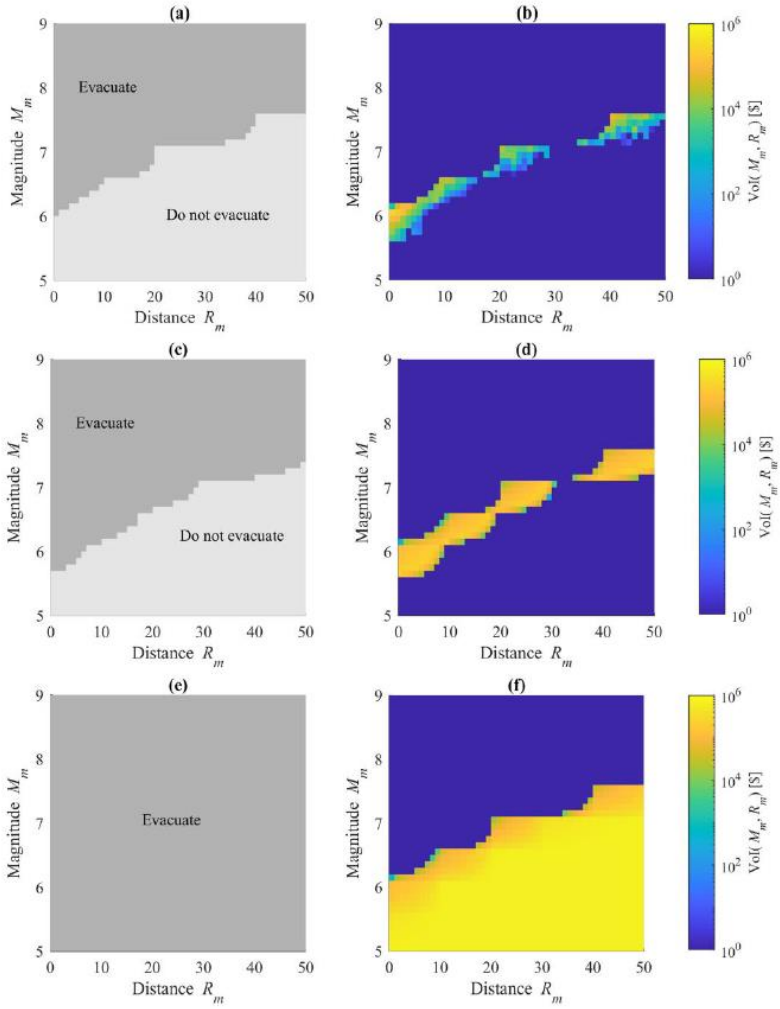


Figure 26: Results of the VoI implementation (Giordano, et al., 2023)

The detailed example can be reviewed in (Giordano, et al., 2022)

6.4.2 Case study – SS114 bridge of motorway E45 Sicily Italy

The framework presented in the numerical example above, is adopted in the work of Giordano & Limongelli, (2020) for the assessment of the utilization of a seismic SHM system. The subject of study is a 178m composite 4 span bridge, located at a relatively seismic active area in Sicily. The bridge is part of the E45 route.

Three different damage states were considered namely DS1 no or minor damage DS2 serious damage and DS3 upcoming failure. The actions have a binary character and are “Keep open” and “Close”. Also, an assessment regarding the optimum source of information is explored. The two sources of information regarding the structure’s condition are visual inspection and SHM system. For this application the costs related to the failure are considered direct, while the costs related to the shutdown of the bridge are considered indirect.

The results are similar to the ones presented above. The maximum value of VoI arises when the optimal action is not evident. The additional information obtained due to the system’s

operation facilitates the decision-making procedure. However, it is not so powerful and influential when the costs present great discrepancy.

Regarding the subject of the optimal source of information, visual inspection constitutes the preferred source of information when the direct costs are greater or approximately equal to the indirect costs and the ratio of the cost of SHM system to the cost savings (VoI) is relatively high i.e. close to 1.

6.5 COST ACTION TU1402

EU is facing ageing infrastructure assets, stakeholders unwilling to invest in SHM systems and lack of standardization regarding the implementation of SHM systems. In comparison with the rich scientific research regarding SHM systems, practical implementation cases are limited (-COST-, 2014).

COST TU1402 is an action of EU for the quantification of the value of SHM. TU1402 aims at development, through advancements utilizing SHM systems. Action started in 2014 and finished by 2019. Among the deliverables of the action are scientific papers, attempting to bridge the gap between scientific research and practice. During the active years TU1402 produced 80 articles regarding the employment of VoI. Details regarding the articles can be found at https://www.cost-tu1402.eu/.

Additionally, one more significant deliverable of the action is guidelines. The lack of standardization in the field of SHM, is one of the reasons obscuring their wider adoption. Thus, TU1402 produced three kinds of guidelines targeted at different stakeholders.

- Guidelines for operators (Sousa, et al., 2019)
- Guidelines for practitioners (Diamantidis, et al., 2019)
- Guidelines for scientists (Thons, 2019)

The reference to this specific action is because the deliverables of the action offer a solution to challenges regarding SHM systems implementation.

6.6 Alternative measures

Chadha, et al., (2021) investigated another metric to assess the benefit of an SHM investment. Instead of assessing only the cost savings to decide upon the implementation of the system, they proposed a ratio of the rewards of the system to the risk associated with the system. This ratio is *the reward to risk* ratio. It is noted that both the reward and the risk are expressed in monetary values. Strictly referring to the definition of VoI by the maximum utility theorem, the cost related to the investment is not taken into account during the computational procedure. Thus, the method proposed aims to overcome this challenge. The framework of the method is presented in a simplified way:

- Cost savings $C_{saving}(z)$ are computed employing the framework of VoI as presented above.
- Cost associated with purchase, installation, operation and maintenance is estimated. This quantity is the cost of investment C(z)

- The ratio $\lambda = \frac{Csaving(z)}{C(z)}$ is the reward to investment ratio
- Assessment of investment's feasibility is based on the following hypothesis: $\begin{cases} \lambda > 1, & \text{feasible} \\ \lambda < 1, & \text{non feasible} \end{cases}$
- In case of more than one feasible SHM solutions the method can be expanded to compare the different solutions.

To demonstrate the proposed framework a case study is carried out. The object of the study is the Greenup miter gate, at Ohio River USA. The damage examined is the gap between the gate's edge and the respective wall. Based on the value of this quantity, the gate can be classified into different damage states. For the sake of simplicity, authors treated damage classification as a binary example and the two possible damage states are either not damaged or damaged. Furthermore, the operator's actions are considered binary. The operator will either close the structure or keep it open. One interesting novelty of this demonstration is the cost function estimation considering the risk-profile of the manager. The authors state that estimation of the costs related to the actions depends on the operator's perception of risk. As for the source of information, three different scenarios are considered (i) no information (ii) information from diving campaigns (iii) measurements after the removal of water from the navigation lock. The results are presented in the following table.

Table 12: Numerical results

Source of information	C(z)	Csaving(z)	λ
i	0	0	N/A
ii	0.02	0.139	6.95
iii	0.200	0.231	1.155

Source: Chadha, et al., 2021

It is evident that the data acquisition method resulting in greater economic savings is the 3rd one. However, if the costs of these methods are considered, the 2nd method seems more appropriate according to the results of the reward to risk ratio. The same conclusion can be reached if the cost of data acquisition is subtracted from the cost saving.

An additional method has been proposed by (Marsili, et al., 2024), which is based on the minimum detectable difference of a damage component. Instead of performing computations for all the possible monitoring outcomes, the computational procedure is simplified by considering only the quantity of the minimum detectable alternation of a component. For more information regarding this analysis the readers are referred to (Marsili, et al., 2024).

7. Case studies

This chapter presents case studies from infrastructure projects mainly in Greece. An example from abroad is presented as well.

7.1 Dams

7.1.1 Mornos' dam

Mornos' dam and the respective reservoir are located in the regional unit of Fokida, Greece, near the town of Lidoriki in the bed of the river Mornos. The scope of the project was the construction of an earthen dam (Figure 27) in order to cover the increasing water demands of Athens. The contractor of the project was Proodeftiki S.A. (Proodeftiki S.A., n.d.). The early construction activities started in 1969 and were completed in 1979 (EYDAP S.A., n.d.). The dam's technical characteristics are presented in the following table.

Table 13: Mornos' dam characteristics

Characteristic	Value
Type	Earthen with clay core
Crest height	126m
Crest level (a.s.l)	+446.5m
Flood level (a.s.l)	+443.5m
Crest width	10m
Crest length	815m
Crest slope	1:2,4 Upstream 1:2 Downstream
Reservoir surface	19,9 km2
Max. reservoir volume	764 10^6 m3
Max. usable reservoir volume	630 10^6 m3

Source:EYDAP S.A.

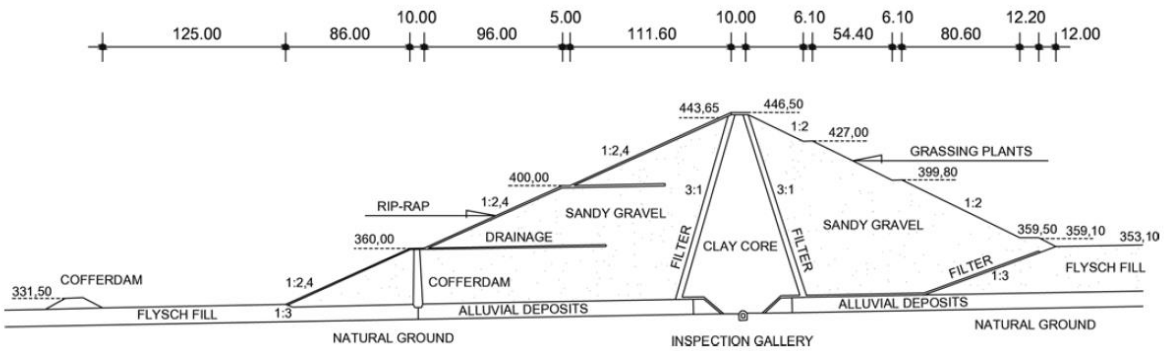


Figure 27: Cross section of Mornos' dam (Gikas & Sakellariou, 2008)

At this point it is considered important to make a reference to the geological conditions of the area. The two main rock types dominating the area are the flysch and limestone, the former being considered impervious and the latter pervious (Nana, 2013). In fact, at the areas where limestone is found, waterproofing measures were carried out (Gikas & Sakellariou, 2008; EYDAP S.A., n.d.).

Due to the geological conditions described above and the dam's characteristics the establishment of a monitoring scheme was of great importance (Gikas, et al., 2005). The instruments utilized are both geotechnical and geodetic. The geotechnical instruments installed are extensometers, piezometers, earth pressure cells and accelerometers. The geodetic network established consists of 15 reference points and 53 control points. Geodetic measuring campaigns included both traditional measurements and measurements with satellite methods (Gikas & Sakellariou, 2008).

Settlements are considered one of the most common deformations based on the construction materials and the type of the dam. Thus Gikas & Sakellariou (2008) present a detailed analysis of settlement assessment for a period over 30 years. This period covers the construction, 1st reservoir filling and most of the operational phase. Results derived from geodetic and geotechnical instruments display similar trends regarding the settlements. The absolute magnitude of vertical displacements increases over time, but it tends to stabilize. This is evident in Figure 28.

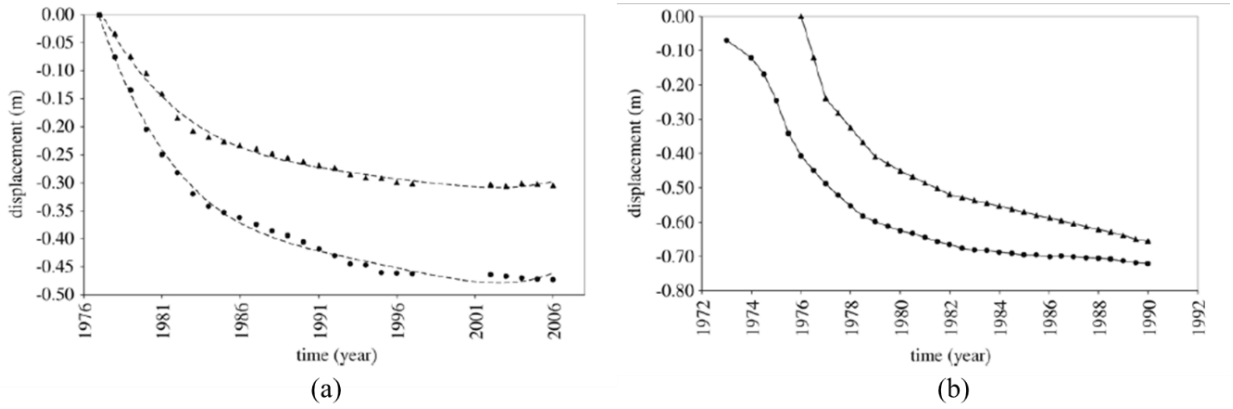


Figure 28: Vertical displacements (a) at the crest level and (b) internally. For case (a) circles refer to the middle of the crest while triangles refer to the end of the crest. For case (b) circles refer to the bottom layers of the dam while triangles refer to the top layers of the dam (Gikas & Sakellariou, 2008)

One more important aspect covered by the work of Gikas & Sakellariou (2008) is the verification of the parameters used in the FEM for the deformation assessment and the risk failure. Even though the magnitudes of the displacements presented differences, the trends were similar leading to verifying that FEM estimations are correct.

7.1.2 Ladonas' dam

Ladonas' dam is located in the regional unit of Arcadia, in Peloponnese, Greece. The river filling the reservoir is Ladonas river, a tributary of Alfeios river. Contractor of the dam was an Italian company, as the project was part of the Greece's compensation program for World War II. The construction period was between 1950 and 1955 (Pytharouli & Stiros, 2004). Nowadays, the main use of the dam is for energy production, while it covers irrigation and water supply demands (DEI S.A., n.d.).

Table 14: Ladonas' dam characteristics

Characteristic	Value
Type	Concrete
Crest height	+56m
Crest length	101.5m
Reservoir surface	4 km2
Usable reservoir volume	46.2 10^6 m3

Source: Pytharouli & Stiros, (2004); DEI S.A., (n.d.); Stiros, et al., (n.d.)

A geodetic network was established for the monitoring of both horizontal and vertical displacements. The geodetic network contains 6 control points located on the crest and 2 reference points located on the left and right abutment (Figure 29).

Figure 29: Geodetic network of Ladonas' bridge. The positions are approximate (Image source: https://www.iefimerida.gr/)

Apart from the computation of displacements, for assessing the structural integrity of the dam, the field data from Ladonas' dam were utilized for the correlation of the displacements' magnitude and the reservoir level. It is expected that the higher the reservoir level, the higher

the hydrostatic pressure. Thus, the deformation magnitude increases. Pytharouli & Stiros, (2004) and Stiros, et al. (n.d.) decided to perform a spectral analysis to confirm the above contention. The available data utilized for this purpose was from 1968 up to 2001. The points presenting the greater displacements are 3,4 and 5. This is rational, since the location of these points is in the middle of the crest. The computed vertical and horizontal displacements are presented in Figure 30 and Figure 31**.**

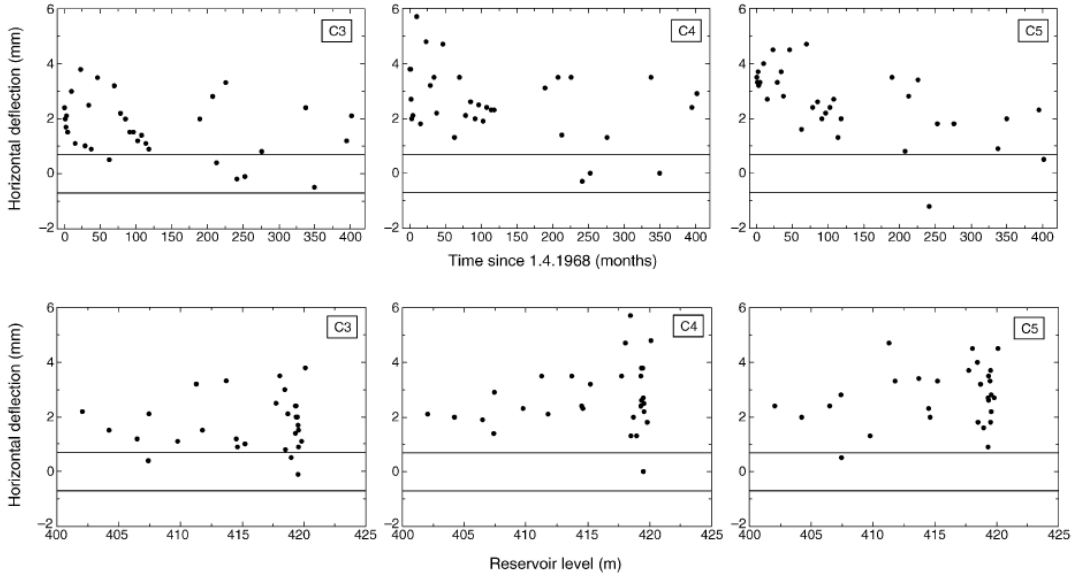


Figure 30: 2D deformations (Pytharouli & Stiros, 2004)

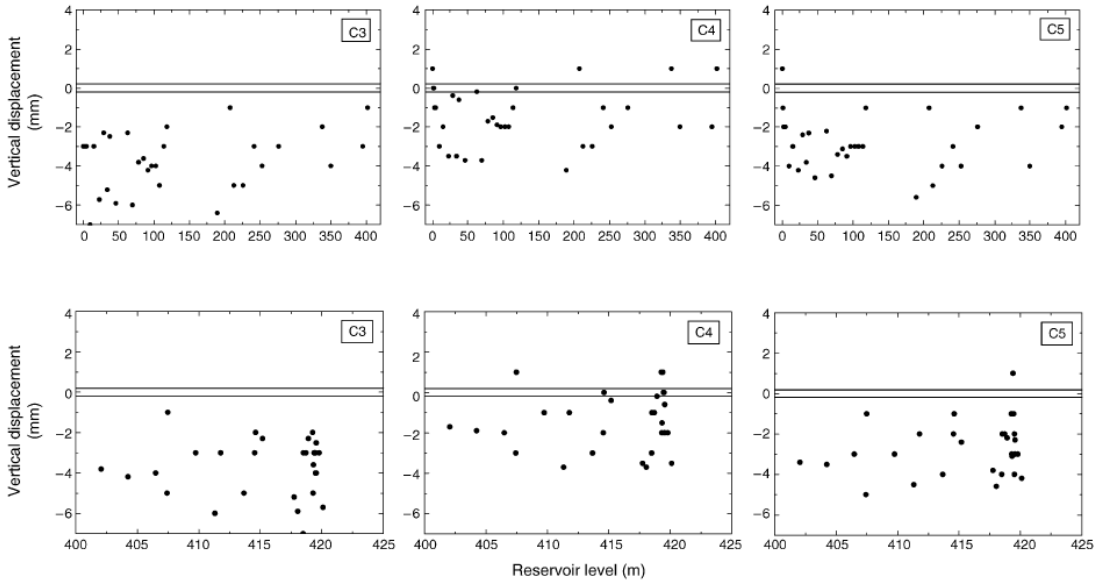


Figure 31: 1D deformations (Pytharouli & Stiros, 2004)

Deformations did not exceed ±7mm and the structural integrity of the dam was considered satisfactory. The most noteworthy result of the research was the correlation between the reservoir level and the deformation variation. The research revealed a 7mm variation in deformation value corresponding to a 20m variation of the reservoir's level, confirming the

initial contention. For more applications of geodetic monitoring networks regarding DEI's dams' assessment the readers are referred to (Stiros, et al., n.d.).

7.2 Bridges

The implementation of SHM systems for bridge condition assessment is the most common application of SHM.

7.2.1 Charilaos Trikoupis bridge

Charilaos Trikoupis bridge or as it is commonly known Rio – Antirio bridge is one of the most innovative structural achievements in Greece. The idea of bridging Peloponnese with Central Greece belongs to the great visionary Charilaos Trikoupis. The execution of his idea takes place one century later with the tender phase starting on 1991. The opening ceremony after the project's completion takes place in 2004 (Charilaos Trikoupis Bridge, n.d.). A short timeline is presented in Figure 32 below.

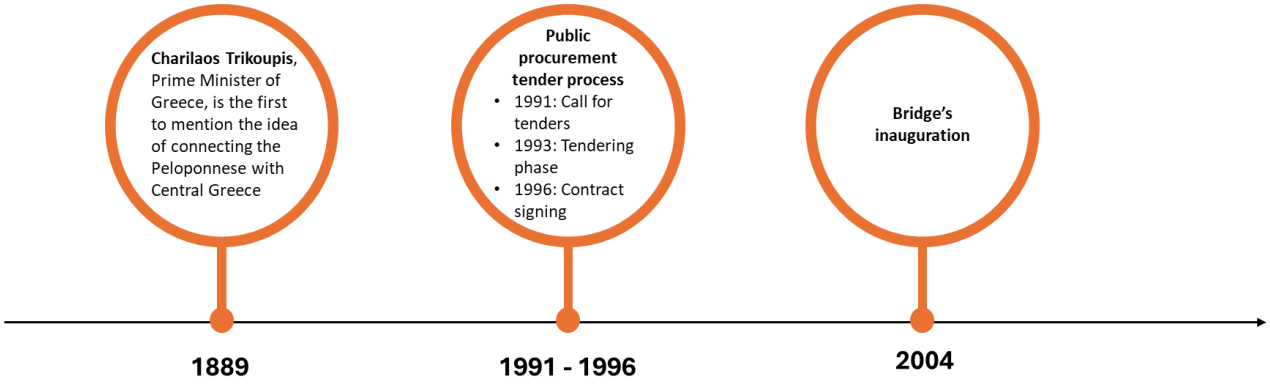


Figure 32: Charilaos Trikoupis bridge timeline

As for the technical aspects of the structure, the project is a cable stayed bridge with multiple spans. The deck is suspended by 368 cables anchored to the top of 4 piers (Figure 33). The technical characteristics of the bridge are presented in the table below.

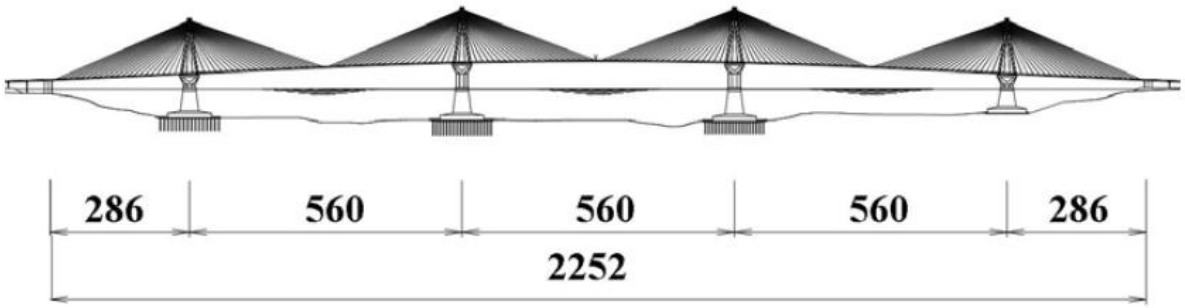


Figure 33: Charilaos Trikoupis Bridge view (Papanikolas, et al., 2009)

Table 15: Technical characteristics of Rio - Antirio bridge

Characteristic	Value - Description
Total Length	2252m
Span 1	286
Span 2	560
Span 3	560
Span 4	560
Span 5	286
Foundation	Reinforced concrete pads 90m diameters reinforced with metallic inserts
Pier	Height: 189 up to 227m Bottom part: Cone with bottom diameter 38 and top 26 m Middle part: Octagonal shaped structure Top part: Octagonal shaped pyramid with 15m height
Pylon	On the top of piers. 38m square base with 4 reinforced concrete members
Deck	Width 27.2m Steel concrete composite structure
Cables	368 cables Length: 79 up to 295m Inclined stay cables linked to the pylons and the side of the deck

Source: Papanikolas, et al., (2009)

The design and construction of the bridge were complex and difficult tasks due to the various adverse conditions that prevail in the area (Charilaos Trikoupis Bridge, n.d.). More specifically:

- Great length (≈ 2500m)
- Great depth reaching even 65m
- Intense winds
- Intense tectonic activity
- Marine navigation
- Geological adverse conditions

The last four bullets remain important issues which need to be taken into consideration during operational phase to ensure the functionality and safety of the bridge (Charilaos Trikoupis Bridge, n.d.).

Apart from a technical innovation, Rio – Antirio bridge is an innovation in terms of instrumentation. The challenges mentioned above posed significant concerns to the managers, leading them to develop a structural risk assessment manual, taking into consideration these adverse conditions. The result of this assessment was the establishment of special inspections and the instrumentation of the bridge, apart from the visual inspections. Papanikolas, et al., (2009) present bridge's tailored management system based on information received from three different sources:

- Visual inspection
- Special inspection, i.e. material inspection
- Monitoring

The company Advitam designed and installed the Rio – Antirio bridge monitoring system which is called WEASHM. The system is equipped with over 100 sensors and survey points. The sensors are located on critical parts of the bridge. More specifically sensors are placed on:

- Cables
- Piers – Pylons
- Deck
- Expansion joints

The data regarding the structure's dynamic response is pre-processed from special equipment located on the pillars and they are transmitted through a network of optical fibers. Apart from that, environmental factors are monitored such as temperature, wind speed, etc.

The four layer SHM system of the bridge consists of sensors, power supply and signal transmission system, digitalization and pre-processing, data transmission and management

7.2.1.1 Sensors

The conditions prevailing in the area and the risks identified during the risk assessment procedure define the parameters required to be monitored and the instruments/sensors which need to be utilized. Due to the intense winds and seismic activity, velocities and accelerations are two parameters monitored. Also, this specific type of bridge denotes that the cable forces should be monitored. The following table summarizes the parameters monitored and the respective sensors utilized (Papanikolas, et al., 2009).

Table 16:Parametres and respective sensors of Charilaos Trikoupis Bridge

Parameters	Sensors	Number of sensors
Acceleration of the deck	Accelerometers	15
Ground acceleration	Ground accelerometers	2
Acceleration of the piers	Accelerometers	12
Acceleration of cables	Accelerometers	13
Cable forces	Load cells	16
Variations of expansion joints	Magnetic extensometers	2
Forces of the connections between deck and piers	Strain gauges	4
Ambient temperature		
Deck & Road temperature	Temperature sensors	4 for the road 5 for the deck

Wind velocity	3d meteorological stations	2

Source: Papanikolas, et al., (2009)

7.2.1.2 Power supply and signal transmission

The sensors are grouped according to their location on the structure. For each sensor group, a corresponding power supply panel board is provided. Beyond power supply, these panels also serve as "collectors/receivers" of the analog signals generated by the sensors (Papanikolas, et al., 2009) .

7.2.1.3 Digitalization and pre-processing

The analog signal needs to be transformed into digital signal. This process as mentioned above is executed at special devices located at the four piers of the bridge. Furthermore, an initial pre-processing is carried out (Papanikolas, et al., 2009).

7.2.1.4 Data transmission and management

For the real-time assessment of the structure's condition, a reliable data transmission system is established. The system relies on a network of double optic fibers. Moreover, the processed data are permanently stored and serve as a basis for future comparison (Papanikolas, et al., 2009).

7.2.1.5 Type of records

The system produces two types of records:

- Historical records: Historical records contain the mean values of the parameters monitored. Historical records are produced on daily, weekly, monthly or annual basis according to the records density, which decreases respectively. Historical records offer data for the assessment of the influence of environmental factors and material degradation on the bridge (Papanikolas, et al., 2009).
- Dynamic records: Dynamic records capture all values of the parameters under monitoring. The recording procedure can be either automatic with a predefined recording rate, or it can commence after the occurrence of an extreme event or after the decision of the bridge's manager. Dynamic records offer data for the assessment of the bridge's dynamic and seismic behavior (Papanikolas, et al., 2009).

7.2.1.6 Software

For the interpretation of the data, the configuration of the system and communication with both the data loggers and the operations center, specialized software is utilized (Papanikolas, et al., 2009).

7.2.1.7 System's future objectives

In order to increase the system's efficiency and effectiveness the following objectives need to be achieved.

- Data reduction: The volume of the recorded data should be optimized in order to provide the "right" quantity of data
- Autoconfiguration of the monitoring scheme based on the type of loading
- Detection and automatic notification both under regular operating conditions and during emergency events

Bridge's SHM system has been proven a remarkable tool for asset management, since it enables quick evacuation and actual mitigation measures during damage events were based on system's data.

7.2.2 Bridges of Egnatia Odos

Egnatia motorway is the biggest highway in Greece located on North Greece. It crosses four regions namely (i) Epirus, (ii) West Macedonia, (iii) Central Macedonia and (iv) East Macedonia & Thrace with a total length of 670km. Bridges which reach a total number of 1856, cover a length of 42km, which is approximately 6% of the total length. For the efficient and safe operation of the bridges, a manual regarding visual inspection of bridges exists (Egnatia Odos S.A., 2013). The manual presents in detail the visual inspection parameters, which need to be taken into consideration. Due to limitations of visual inspections and Egnatia Odos bridges' characteristics (great lengths, located on intense terrains with big height differences, etc.) the implementation of a SHM system constitutes part of the Bridge Management System (Panetsos, et al., 2005).

In order to amplify the utilization of instrumented monitoring systems, EOSA decided to equip some "representative" bridges. The decision criteria for the bridge selection are:

- Characteristic construction method, i.e cantilever or precast beams
- Characteristic pier and deck connection, i.e with bearings or monolithically connected
- Accessibility for execution of construction works of installation
- Seismicity of the wider area

Based on the aforementioned criteria, initially two bridges were selected as sufficiently representative. These bridges are G2 and G9, whose location is presented in Figure 34 Panetsos, et al. (2005) and Lekidis , et al. (2009) present the instrumentation procedure and results of monitoring these two bridges.

Figure 34: Egnatia Odos. Orange circles indicate the locations of G9 and G2 bridges respectively, from left to right (Lekidis , et al., 2009)

7.2.2.1 Bridge G2 (Kavala)

Bridge G2 is located at Kavala's bypass, in East Macedonia & Thrace region. It has two carriageways (left and right). Technical characteristics of the bridge are presented in the following table:

Table 17: Technical characteristics of G2 bridge

Characteristic	Value / Description
Piers	3 middle piers 2 abutments
Construction method	Precast, pretensioned concrete I beams
	Cast in situ piers
	Cast in situ deck
Beam length	45m
Deck length	170m continuous deck
Joints	2 elastometallic joints at abutments
Connection	Elastometallic bearings

Source: Lekidis , et al., (2009)

Initially the structure was equipped with an accelerometer network. Four record units were purchased, in order to capture bridge's ambient dynamic response. The maximum possible number of sensors was determined by the capabilities of the selected record units. Each record unit had the ability to cover 12 sensors. Thus, 48 accelerometers is the maximum number of sensors that the systems is able to cover. After appropriate investigation, a total number of 24 sensors was considered sufficient. Moreover, only one carriageway was equipped. Sensors were placed at location considered as suitable for capturing the critical responses, for example at bearings locations. Sensors and record units connected with wires. Construction works associated with network installation contained among others platform construction for the inaccessible locations, special arrangements for sensor protection, etc. (Lekidis , et al., 2009)

Time-series of bridge's accelerations were collected and processed via a special software for the estimation of bridge's modal properties. From this experimental procedure one important outcome is the deviation between the theoretical values realized during the design phase and the actual values captured with the SHM system. This deviation arises from the difference of bearing's behavior, minor differences in other realizations and environmental variations, however the last cannot be considered as the sole reason for the deviation.

7.2.2.2 Bridge G9 (Polymylos)

Bridge G9 is located at Polymylo – Leukopetra road section, in Kozani region. It has two carriageways (left and right). Technical characteristics of the bridge are presented in the table below:

Table 18: Technical characteristics of G9 bridge

Characteristic	Value / Description
Piers	1 middle pier 2 abutments
Construction method	Cantilever (T shaped with varying height)
Length	170m (85m each cantilever)
Connection	Middle pier monolithically connected
	Elastometallic bearings at abutments

Source: Lekidis , et al., (2009)

The instrumentation strategy adopted for this bridge is the same as G2 bridge (same type and number of sensors, same connection with the record units, same construction activities). The only difference between the two monitoring systems is that G9's systems is able to record, additionally, seismic excitations because of sensors located at the base of the middle pier. Finally, the same results as G2 bridge were obtained.

G9 bridge has been also monitored experimentally utilizing GNSS receivers. More specifically, 6 receivers with a record frequency of 1s have been placed in pairs on bridge's deck. This experiment was conducted under normal operational conditions (Pantazis, 2020).

It is noted that due to the inability to identify more up-to-date references, some properties of the above systems may have been altered.

7.2.2.3 Metsovo Bridge

Metsovo bridge is the highest bridge of Egnatia Motorway as the height of the middle pier is 110m. Metsovo bridge is a concrete pre-stressed bridge and the construction method adopted was the cantilever method. The technical characteristics of the bridge are presented in the table below (Stathopoulos, et al., 2010).

Table 19: Technical characteristics of Metsovo bridge

Characteristic	Value
Total length	537m
Span 1	44.78m
Span 2	117.87m
Span 3	235m
Span 4	140m

Pier 1 height	45m
Pier 2 height	110m
Pier 3 height	35m
Deck Width	13.95m

Source: Stathopoulos, et al., (2010)

The monitoring system installed on the structure after its completion contains the following sensors:

- 12 acceleration sensors
- 16 strain sensors
- 12 temperature sensors
- 1 wind velocity sensor

The above sensors constitute the permanent monitoring network, while it is noted that during the various construction stages mobile sensors were deployed

7.3 Tall buildings

In this chapter the SHM system of Burj Khalifa is presented, due to inability of finding references regarding Greek tall buildings.

7.3.1 Burj Khalifa

Burj Khalifa located at UAE is the tallest building ever constructed, and it has also a novel SHM system procedure. The technical characteristics of the structure are presented in the following table (Abdelrazaq, 2011)

Table 20: Technical characteristics of Burj Khalifa

Characteristic	Value
Height	828m
Levels	162 above ground floors 3 basements
Material	From basement - 156 floor: Reinforced Concrete From 156 floor - top point: Steel
Foundations	Central concrete reinforced pile 3700mm diameter Reinforced concrete bored piles 1500mm diameter
Area	460000 m2

Source: Abdelrazaq, (2011)

Due to its exceptional height and the lateral loads endured, the structure is equipped with an SHM system. 4 discreet monitoring parts (Figure 35) are identified from the commencement of construction until structure's operational phase.

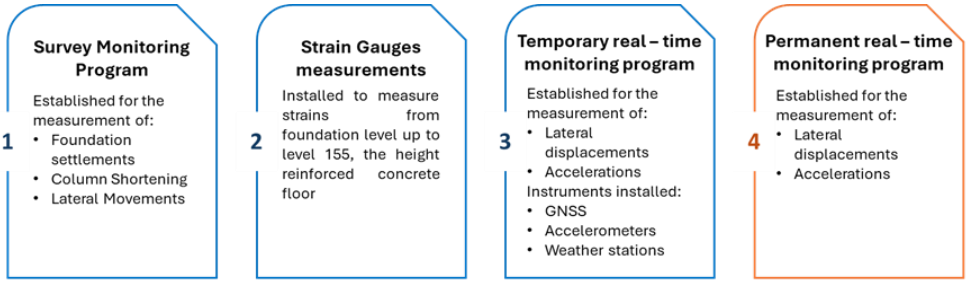


Figure 35: 4 monitoring programs of Burj Khalifa. With blue color the programs established for monitoring during construction.

The first two monitoring programs, though relative are not presented in this thesis. Object of main focus is the permanent real-time monitoring program, while the temporary is described as it constitutes the forerunner of the permanent program.

7.3.1.1 Temporary real-time monitoring program

The aim of the temporary real-time monitoring program was to capture (i) accelerations, (ii) lateral displacements and to capture also environmental factors. Lateral displacements were captured with the use of GNSS system, while environmental conditions were captured from the installed weather station. The system is presented in Figure 36. The installation of the temporary system executed by Samsung was the basis for the permanent monitoring system. It is noted that the temporary system provided useful insight during a seismic event in Iran (Abdelrazaq, 2011).

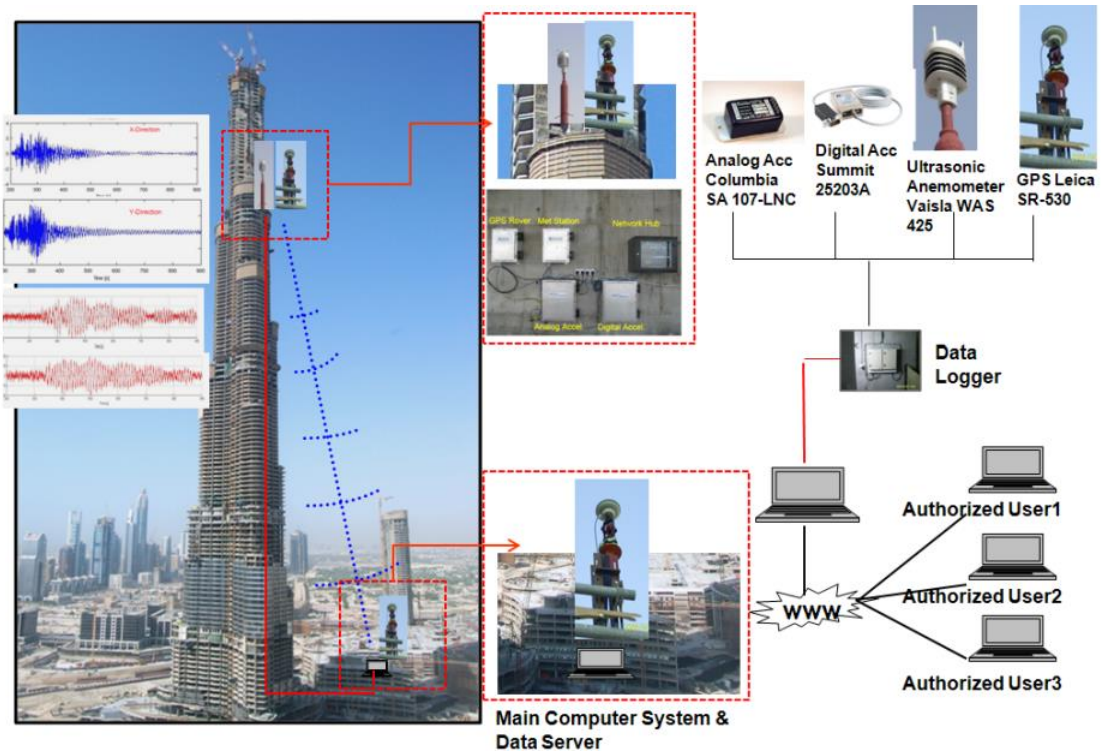


Figure 36: Temporary SHM system of Burj Khalifa (Abdelrazaq, 2011)

7.3.1.2 Permanent real-time monitoring program

The permanent monitoring system (Figure 37) of Burj Khalifa records (i) accelerations, (ii) displacements (iii) wind properties, (iv) dynamic response, while it also provides time-series of the captured data. For this purpose, Burj Khalifa is equipped with:

- 9 pairs of accelerometers (3 at base level and 6 at 73,123,155,160M3, Tier23A and two of pinnacle levels)
- GNSS system equipment
- 23 sonimometers
- Weather station

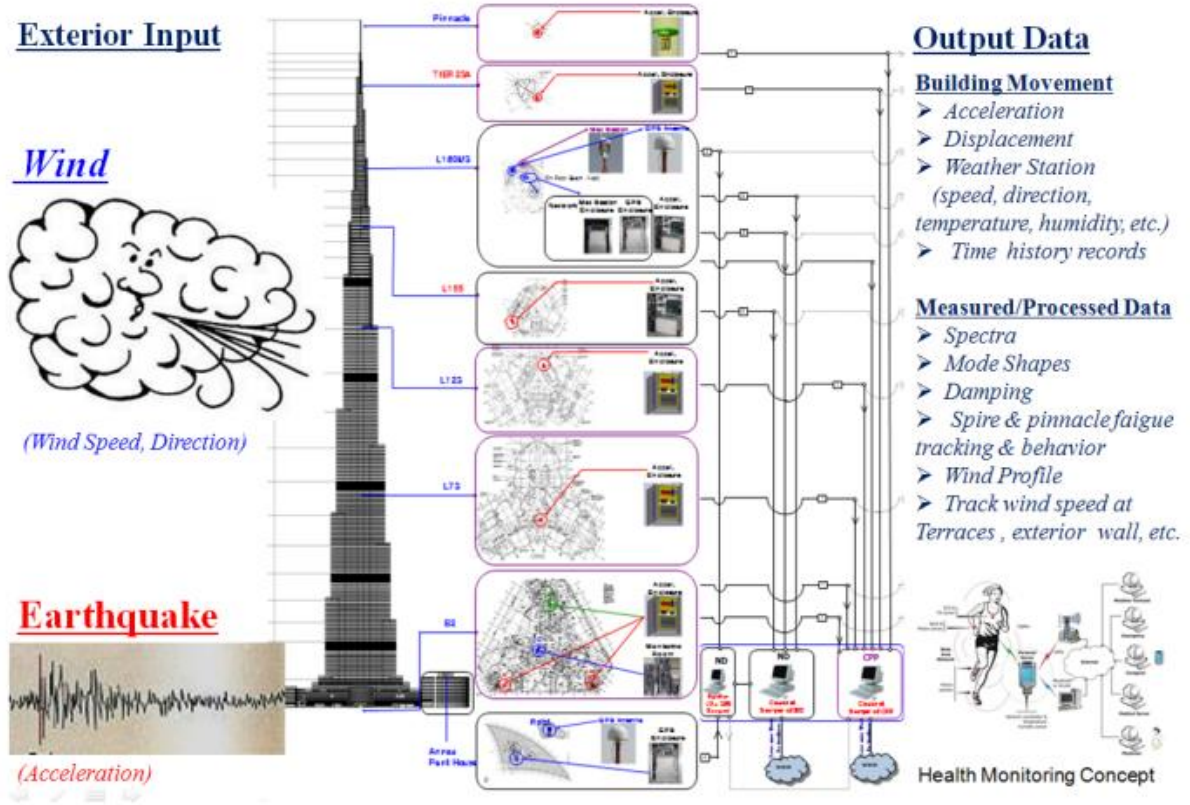


Figure 37: Permanent SHM of Burj Khalifa (Abdelrazaq, 2011)

System's results have been used to compare structure's actual behavior with the predicted one, in order to verify realizations made during design phase. Moreover, they are exploited for early detection and warning. (Abdelrazaq, 2011).

7.4 Sports Facilities

Structural monitoring of sports facilities is considered crucial due to the concentration of a large number of people. In literature scarce references were found which sufficiently present the application of SHM systems on sports facilities in Greece. However, two big Greek stadiums are monitored with the help of established geodetic networks. These stadiums are (i) Georgios Karaiskakis stadium and (ii) Peace and Friendship stadium. Both of them are in

the wider area of Faliro, where adverse geological conditions are encountered (Papamikidi, 2013). Consequently, monitoring especially of vertical displacements is required.

7.4.1 Peace and Friendship Stadium

Peace and Friendship Stadium located in Neo Faliro, Piraeus, is a complex sports facility. One of the most interesting elements of the structure is the suspended roof of the stadium with the respective concrete ring. The ring is connected to 32 concrete cantilevers. Bleachers are supported by concrete beams. Columns receive the roof and bleachers loads from the cantilevers and beams respectively (Georgopoulos, 2011) .

Project's timeline was from 1977 – 1984. Right after its completion and commencement of operation geodetic control networks were established to monitor the structure's behavior. It is noted that the wider area is characterized by adverse geological conditions. The initially established geodetic networks (1985) consisted of:

- 1D Network: 18 points (8 located to the stadium's access level, 4 at selected cantilevers and 6 at the base of selected columns)
- 2D Network: 12 points (8 located to the stadium's access level and 4 at selected cantilevers)

Four measuring campaigns were conducted from 1985 up to 1995. The outcomes of these campaigns detected vertical displacements at 4 cantilevers (Pantazis, 2020).Throughout the years the initial monitoring networks have been populated (Papamikidi, 2013). Furthermore, stadium was monitored after 1999 Athens earthquake, in order to assess its condition after this emergency event (Georgopoulos, 2011). For this application 2D monitoring network was utilized. The network entails 12 reference points and 18 control points located on critical elements of the structure, i.e. concrete ring. An indicative placement of network's points is presented in Figure 38.

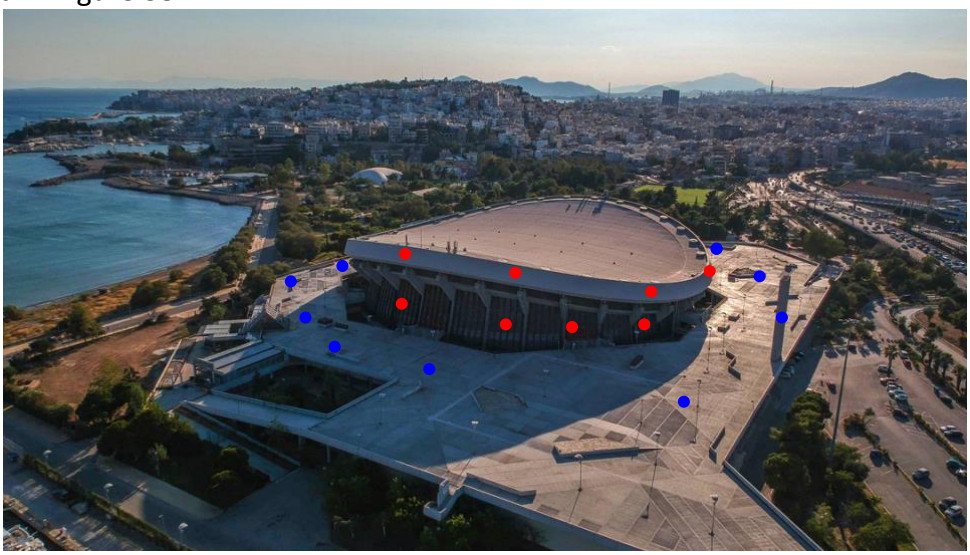


Figure 38:Indicative placement of network's points. Blue: reference points,Red: control points(Image from: https://www.voria.gr/)

From this monitoring campaign, displacements of the concrete ring were detected. This information was then further exploited for the stadium's restoration, while it was also used

for a correlation of the displacement's azimuth with the earthquake's properties (Georgopoulos, 2011).

7.4.2 Georgios Karaiskakis Stadium

Georgios Karaiskakis Stadium located in Neo Faliro, Piraeus, is in the position of the previous Georgios Karaiskakis stadium which was demolished in order to construct the new stadium for Athens Olympic games 2004. Pits dimensions equal to 74m×105m, while the whole stadium's dimensions equal to 200×160m (Avax, n.d.). One of the most interesting elements of the structure is roofing. PVC waterproofing membrane on a secondary steel frame constitutes stadium's roofing system. Roof is suspended by 14 metal cantilever trusses (MakMax, n.d.).

For monitoring purposes geodetic control networks were established in 2005. The two networks established were (Pantazis, 2020):

- 1D Network: 9 reperes
- 3D Network: 12 points (6 points around the stadium and 6 on the outside of the bleachers)

For 1D network 2 measuring campaigns were conducted in March 2006 and December 2007. From the monitoring campaign displacements with a magnitude of 5mm-16mm were detected.

For 3D network 3 measuring campaigns were conducted in December 2006, May 2007 and March 2010. From the measuring campaigns, horizontal displacements were detected (Pantazis & Lambrou, 2016). It is noted that measuring campaigns took place while the stadium was empty and while the stadium was filled with audience in order to assess audience load's influence.

7.5 Tunnels

Monitoring of tunnels during construction phase is a common application as it provides warning for abnormal settlements and enhances safety. Deformation monitoring during construction of S2 tunnel of Egnatia Odos is such an example (Karamitsos, et al., 2006).

As for monitoring during operational phase, the monitoring system of Aktio – Preveza tunnel is presented.

7.5.1 Underwater tunnel of Aktio – Preveza

The underwater crossing connecting Aktio (Central Greece region) with Preveza (Epirus region), is a unique structure as it is the only underwater tunnel of Greece. The underground part of the project consists of:

- Underwater tunnel
- Underground access ramps

Technical characteristics of these two sections are presented in the bellow table:

Table 21: Technical characteristics of underwater tunnel

Characteristic	Value / Description
Length	909m
Cross-section	Orthogonal (5.35m x 10.60m)
Construction method	Precast segments
Segment dimensions	134.5m length 1m wall thickness
Segment weight	15000 tones

Source:EOSA, (2021)

Table 22: Technical characteristics of underground access ramps

Characteristic	Value / Description
Length	172m Aktio side
	509m Preveza side
Cross-section	Orthogonal (5.35m x 10.60m)
Construction method	Cut & Cover

Source:EOSA, (2021)

The monitoring scheme of the underwater tunnel consists of two parts (i) periodic geodetic measurements (ii) permanent installed sensors. It is noted that EOSA has published a manual regarding project's management during the period 2021 – 2026. Based on this manual the monitoring system of the tunnel is described (Egnatia Odos S.A., 2021).

7.5.1.1 Geodetic measurements

Regarding geodetic measurements, vertical displacements are the quantities of interest. Geometric levelling method is the one adopted along with the use of digital levels and barcoded staffs. Furthermore, the manual gives specific instructions regarding measuring procedure. Specifically, it defines:

- Time of measurements: Measurements are conducted during night period possibly in order not to disturb tunnel's operation and not to set in danger the personnel
- Step of geometric leveling
- Closure error and adjustment instructions

Measuring campaigns have a time interval of one year as it is considered that the main cause of potential displacements are seasonal phenomena. However, in case of an emergency event, measurements will be executed.

7.5.1.2 Permanently installed sensors

Apart from periodic geodetic measurements, permanently installed sensors are continuously operating. Specifically, 4 accelerometers recording 3D acceleration, 44 jointmeters and 4 moisture and temperature sensors are installed in the tunnel. Jointmeters and sensors

capturing environmental effects operate and record continuously, while accelerometers are continuously operating and start recording after the exceedance of predefined threshold for ground acceleration

Finally, the referred manual provides for the inspection of the monitoring systems and their replacement after the end of their service life.

8. Conclusions

The present thesis investigates the fundamental concepts of SHM and analyzes traditional monitoring methods. Focus is given to geodetic monitoring methods, integration of new technologies, the so-called Construction 4.0. technologies, and the examination of SHM systems' value through a decision-making framework. For this investigation a literature review was conducted, which enabled the creation of an overview of the current state and future trends of SHM both in Greece and abroad. The conclusions reached after this comprehensive examination are presented below.

One of the main reasons obscuring SHM's wider practical adoption is their cost along with limited understanding of the system's benefits. For the quantification of SHM value, both for operational and emergency management, the concept of VoI is proposed. VoI enables the selection of optimal maintenance actions and demonstrates the benefits of data-driven decision making instead of experience-based decision making. However, most of the examples explored, which utilize VoI method, are binary and thus do not display the actual state which is more complex.

Moreover, significant reasons hindering SHM adoption are technical and computational challenges associated among others with large volume of data, leading to increased storage demands and advanced computational algorithms demand. Construction 4.0. technologies, offer noteworthy solutions to computational and technical challenges. Case studies demonstrate that new technologies can enhance data acquisition, processing and storage through various technologies. UAVs combined with appropriate sensors can facilitate data collection from inaccessible and large-scale areas. AI and ML offer remarkable computational opportunities since they allow automated feature extraction and are associated with capabilities such as transfer learning. IoT and clouds offer quick solutions for data transfer and storage, while BIM and digital twin enhance communication between stakeholders who are not familiar with SHM aspects. However, no tangible framework regarding their implementation exists while serious challenges arise such as cyber security issues.

Current state of SHM in Greece was reviewed through case studies of big infrastructure projects. From this review, it is concluded that no unified institutional framework exists, analyzing all aspects and procedures of SHM, beyond technical guidelines of Technical Chamber of Greece (2008), national technical specifications and visual inspections manuals. This state is in contrast with practices adopted by other countries, i.e. China where the binding nature of SHM framework for specific structures aimed at promoting their wider adoption. Furthermore, structures investigated present great heterogeneity regarding their monitoring systems. Partially this deviation is logical due to the different nature and unique characteristics of the structures. Case studies lead to positive results regarding verifying SHM advantages. Among these findings are:

- Geodetic monitoring has been utilized to assess, on global scale and with high accuracy, major infrastructure projects' response (both static and dynamic).
- Use of monitoring data for comparison of actual measurements with design assumptions facilitates identifying deviations, verifying design assumptions and leads to enhanced future designs

- Use of monitoring data for correlation of deformation with causative factors, leads to better understanding of structural performance
- Use of monitoring data allows early warning during emergency events
- Use of system information works as the basis for informed restoration works
- Use of system information enables estimating the condition of similar structures.

The future of monitoring systems is PSHM systems. For this transition use of innovative technologies is required. AI and its subset ML are utilized in order to exploit the Transfer Learning property of ML. Thus, SHM for structures presenting sufficient similarities with structures for which actual data exists, is possible. However, in order to avoid negative effects (Negative Learning) standards should be established providing detailed guidelines and evaluation criteria. In this context, the concept adopted from EOSA for the bridge's G2 and G9 can be considered exceptional, as the bridges instrumented were carefully selected based on their construction method and structural system.

From all of the above it is concluded that monitoring systems:

- Enable comparison between design quantities and actual quantities allowing identification of deviations, verification of design assumptions and enhancement of future designs
- Enable more realistic configuration of physics-based models increasing their predictive reliability
- Enhance emergency management as they offer the required information for early warning when abnormalities regarding structure's actual behavior are detected
- Allow correlation between deformation and causative phenomena, leading to enhanced understanding of structure's actual behavior
- Offer a concrete base for informed decisions and optimal repair actions as they promote focused interventions instead of general repairs
- Promote predictive maintenance as they have prognostic capabilities
- When combined with emerging technologies offer an exceptional tool for improved interpretation and real time visualization, while they enhance communication among heterogeneous stakeholders with no knowledge regarding monitoring concepts
- Enhance cost management as they offer necessary data for informed decision-making. As presented in chapter 6, monitoring data can be used in order to identify optimal actions in terms of cost.
- Enhance risk management as they offer required data for quantitative risk assessment and for updating risk probabilities.
- Transform the experience – based decision-making model to data – driven decision-making model
- Apply at all project phases from initial planning to decommission
- Produce real-time, continuous data which enables more reliable predictive maintenance

- Align with sustainability concepts as they allow the extension of an asset's RUL while reducing nonessential interventions

However,

- Integrating new technologies is associated with risks, even legal risks related to cybersecurity and privacy. Thus, clear and robust standards and guidelines need to be developed.
- Modern systems relate to computational complexity, which may have a negative effect if sufficient data is not provided and acts as an obstacle affecting managers' decisions for implementing these systems.
- Greece's current state is behind current SHM state, while data-driven management appears to be at an early stage. Charilaos Trikoupis bridge is a great example of instrumentation, monitoring and data driven management since it's utilizing SHM data for optimal mitigation measures selection
- Finally, despite the technical and computational advances and excellence of an SHM system, without taking into consideration managerial aspects such as cost, stakeholders management etc. system's implementation is deemed impossible. Thus, SHM should be treated as a holistic approach.

Future research should emphasize on:

- Development of standards and guidelines, especially now that emerging technologies are in the spotlight. Standards will cover both technical and managerial aspects and will relate to specific types of structures and their properties
- Further exploration of the use of emerging technologies in SHM applications by implementing these technologies in real structures
- Further exploration of VoI framework, with more decision parameters in order to model real decision scenarios. Finally, it is suggested to utilize this framework for Greek monitoring programs in order to provide managerial insights regarding monitoring of important infrastructure projects.

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