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Novel, Sustainable Preservation of Modern and Historic Buildings and Infrastructure. The Paradigm of the Holy Aedicule’s Rehabilitation

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ABSTRACT
Modern and historic buildings and infrastructure are subject to varying environments and risk conditions. Their sustainable preservation demands an integrated methodology of diagnosis, monitoring and control, with appropriate interventions, designed, implemented and assessed within a holistic approach that benefits from transdisciplinarity and cooperation between involved scientific and technical fields and stakeholders. The project of the rehabilitation of the Holy Aedicule of the Holy Sepulchre in Jerusalem, can act as an emblematic and successful paradigm that demonstrates a multispectral, multidimensional, novel approach to address the project’s challenges and preserve the monument and the values it represents.

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1. Introduction

Today’s Built-Environment is to a great extent the result of intense construction activity, initiated in the inter-war period, between World War I and World War II, and intensified after the end of World War II with the urban, industrial and technological transformation of Society. Today, almost three-quarters of a century later, a significant percentage of the Built-Environment, especially reinforced concrete built assets, has exceeded its life-expectancy. The threat from the end of the lifetime of the built environment, including historical and contemporary buildings and infrastructure, is of significant socio-economic impact for Europe, a region where historic buildings “coexist” with contemporary ones (Conti 2017). The fact that a large fraction of construction works in Europe regards retrofitting of existing buildings, is indicative of their importance. In fact, in certain European countries, which experienced the negative effects of the recent fiscal crisis, this fraction is even higher, due to the corresponding decrease in new construction.

The natural and man-made deterioration of existing structures; the effect of various environmental actions that influence the durability, bearing capacity and serviceability of structures and their building materials; the challenges of the current socio-economic environment; the need for reliable assessment and a capability to design and implement durable interventions to existing works aiming towards sustainability, all of the above demand Research and Innovation and are matters of high priority, importance and impact on national, regional and international levels.

2. The necessity for an integrated methodology of diagnosis and control for the protection and conservation of modern and historic buildings and infrastructure

As aforementioned, built environment is subjected to a wide variety of threats (WEF 2019; SWD 2017 176 final; GEM 2019; Gill and Malamud 2014; Pilitakis et al. 2014) This fact, in conjunction with the additional and ever-increasing impact from climate change (IPCC 2014a, 2014, 2014), has forced the scientific and technical communities to identify a critical demand for an integrated methodology of diagnosis and control. This methodology must aim to provide a systematic diagnosis of the state of preservation of existing built assets, an assessment of their residual strength and bearing capacity, an evaluation of their resilience (Jigyasu 2014), as well as an assessment of the vulnerability of materials and structures against environmental loads. Such an integrated methodology is essential to support the efficient and economic design, as well as the implementation and post-monitoring of preventive or remedying conservation interventions. The optimum aim must be to improve the resilience of structures and

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their materials in relation to the negative effects of the environment and natural or man-made disasters through time. Moreover, such an integrated diagnosis and control methodology should also preserve and highlight the building's values (historic, social, architectural, etc.), as they can provide crucial data to support the required works. To achieve all the above, which are often contradicting and challenging requirements, optimization of all interrelated stages is necessary.

A critical prerequisite is the adoption of innovative multi-disciplinary approaches, using multi-dimensional and multi-spectral data. Furthermore, the efficient utilization of available research capabilities, infrastructures, know-how, and expertise are beneficial in order to support research and engineering activities in all interrelated fields. These issues apply to contemporary, modern reinforced concrete and historic masonry structures.

Moreover, the "environmental performance" of a building or infrastructure, which is a major criterion of sustainability, is gradually attaining increased importance. This is due to the social requirements for respect to our environment and for the quality of the interior and habitat condition as well as to health and safety regulations regarding inhabitants and visitors and other technical demands. In the case of historic buildings, it is more difficult to achieve an appropriate level of environmental performance, due to the limited degrees of freedom in applying appropriate measures, compared to contemporary structures. Additionally, historic buildings demand detailed compatibility analyses regarding historic and restoration materials, which may further restrain rehabilitation works. These limitations demand innovative and holistic approaches in diagnosis and control, in order to apply appropriate protection and conservation interventions.

2.1. *The support of BIM-type systems towards the preservation of historic and contemporary buildings and structures*

Nowadays, the role and scope of contemporary engineers are under revolutionary reformations. Tools and methods for designing, engineering and constructing building structures are integrated into unified BIM-type systems. Real-time management of the building information and simulation of performances are becoming a crucial decisive step for the development, construction/rehabilitation, and operation of a building. Furthermore, they support an effective and economic maintenance throughout a buildings' lifetime. Recent advancements in big data technologies, Internet of Things (IoT) and Artificial Intelligence (AI), are creating opportunities for the integration, in space and time, of the field-work of engineering. The high-tech analytical and non-destructive capabilities of multi-sensor multi-disciplinary laboratory infrastructures, within unified systems/platforms/tools, can function as scientific support elements, in decision-making processes, regarding maintenance and conservation of existing structures in variable environments and risk conditions.

Such systems/platforms/tools are currently under development or in operation with a (currently) limited level of integration, mainly for contemporary buildings and structures, and to a lesser degree for built cultural heritage assets (Bruno, De Fino, and Fatiguso 2018; Logothetis, Delinasiou, and Stylianidis 2015; Murphy, McGovern, and Pavia 2009), due to the inherent difficulty of the latter. In this work, the use-case of the project of the rehabilitation of the Holy Aedicule (see further below) is presented. The assessment of the current state, the design, and implementation of the appropriate interventions and the monitoring of the works, were performed within a holistic framework. Within this framework, a multi-data/multi-spectral platform was designed and utilized in order to fully exploit the scientific data obtained, not only scientifically, but also as a tool to address the technical needs of the works.

As demonstrated in the paradigm of the rehabilitation of the Holy Aedicule, this BIM-type tool is efficient when it is based on building elements ontologies that are classified in three main categories and parameters

a) Structure related: use/functional requirements, structure/structural performance, form/architectural features, sustainability/environmental performance;

b) Materials related: materiality/texture, aesthetics, properties, techniques and methods of construction, health & safety requirements;

c) Risks and hazards: risk assessment/typology of risks and threats, cost analysis and value engineering.

In addition, this tool provides a semantic analysis and mapping of building elements that can lead to further development of an automated method for an on-site recording and documentation process. With this innovative high-tech diagnostic technologies, a direct preliminary diagnosis of the pathology of cultural heritage assets can also be obtained.

3. The current approaches for sustainable preservation of the built environment

Today, the international scientific research community is making important progress to improve the performance and to increase the lifetime of Built-Environment towards achieving its sustainability. However, documentation, analysis, and redesign methodologies and tools are not yet fully integrated. This can be attributed to gaps in the development of appropriate synergies and procedures, thus hindering the achievement of extensive integration and proper utilization of all available resources (technological, scientific, economic, human resources). Moreover, the methodologies and tools used today are sometimes established on an empiricism approach and not on a scientifically based one, leading to ineffective and economically non-optimized solutions, with negative effects over the total lifetime of a structure. An advanced approach is hindered by the lack of appropriate information regarding the type, range of values of critical parameters, as well as the threshold levels of the performance of structures and their materials, in variable environments and risk conditions, in addition to their synergistic effect.

This is more evident in the case of historic buildings and structures, where the analyses of available or obtained data and measurements are typically conducted within autonomous scientific fields (structure, architecture, geometry, materials). Thus, they usually do not take into account the data and information that derive from interrelated scientific fields. Consequently, a demand emerges to achieve an efficient coupling of data, from different interrelated scientific fields, while ensuring interoperability (Kioussi et al. 2013, 2011). In the international scientific and technical community, the extensive use of non-destructive techniques (NDTs) is highlighted, due to their obvious advantages. However, the parameterization of the results deriving from NDTs, the interoperability of different NDTs, as well as their utilization and management in a georeferenced three-dimensional environment, remains open scientific and technical issues.

There are various factors that negatively affect Built-Environment: the atmosphere (polluted, marine), precipitation, rising damp, salt-decay, floods, usage-related damage, and mechanical loadings (such as abrasion, earthquakes, landslides, frost damage, differential thermal expansion of materials, etc.). Diagnosis, control, and redesign for the effective conservation of historical and modern buildings and infrastructure, demand a multi-dimensional and multispectral assessment and approach. Although some of these factors are contemporary and prevail in specific regions as a result of modern Development (e.g. polluted atmosphere in urban areas), however, others have been acting on historic structures and built Cultural Heritage continually throughout the ages. These should be taken into account, not only during diagnosis, but also when designing appropriate preservation interventions and monitoring their effectiveness.

One important factor is the seismic activity that has influenced the construction technology in various areas around the world. Historically, construction technology in high seismicity regions, has evolved and increased its effectiveness, especially in the last decades, reflecting an improved understanding and prediction capability of the behaviour of structures under seismic loads.

Many older and historic structures and infrastructures survive to this day because they were conceived appropriately and constructed with materials withstanding such dynamic loadings, even without the analytical capabilities of today.

In the last decades, legislation has greatly evolved regarding this important issue. However, a large part of the built-environment has been constructed many decades ago, under different legislations than the current stringent one. Moreover, these structures and infrastructures have been subjected to various past earthquakes without systematic documentation of the sustained damages throughout time.

Modern documentation techniques, analytical and non-destructive testing, as well as computational tools, can provide information regarding the state of preservation of existing structures and infrastructure. However, it is increasingly realized that their interoperability and complementarity are crucial requirements that can provide further unified knowledge regarding the variation of the state of preservation through time (Kioussi et al. 2013). This is crucial for the prediction and assessment of the structure's remaining performance and for the design of appropriate remedying interventions.

The Holy Aedicule rehabilitation project is a characteristic use-case. This historic structure has sustained numerous earthquakes that have had an impact on its current state and dynamic response, but were largely non-documented prior to the initiation of the project. However, the introduction of interoperability and complementarity of the techniques used, permitted a thorough assessment of its current state and an optimum design of appropriate interventions.

It must be emphasized that the built-environment is often at higher risk when ineffective interventions are applied. Historic and contemporary buildings and infrastructures may demonstrate higher vulnerability after the implementation of interventions, if the design and implementation of interventions are not the optimal ones. The use of inappropriate restoration materials (replacement; strengthening; protection) that are physico-chemically and mechanically incompatible with the original ones, can dramatically increase the vulnerability of the retrofitted structure. The utilization of technologies that extensively alter the original structural system of the building or infrastructure and/or are based on concepts that are applied to other structures, without prior validation, can also cause significant damage. This is often the case when limited information is available, regarding the building, its structural behaviour, its materials, and its construction technology/ies. The implementation of inappropriate interventions, can be attributed either to the (sometimes unavoidable) use of incomplete documentation, to the limited analytical capability of the characterization and analytical tools utilized, or due to the adoption of empirical and rule-of-thump approaches. This is especially the case for buildings and infrastructure constructed many decades or even centuries ago, where either documentation — complying to the current standards — is limited or not even available.

It should be noted that modern protection and rehabilitation technologies and current legislation, standards and norms — that have been developed for contemporary buildings and structures — cannot be applied without optimization/adaptation to older structures or built cultural heritage assets. In general, contemporary structures have, to some degree, incorporated, during their design and construction, modern technologies that reduce their vulnerability against environmental hazards. Therefore, modern protection and rehabilitation technologies are highly applicable on modern structures.

In the case of historic buildings and infrastructures, the lack of crucial information, combined with the compatibility issues of modern technologies and restoration materials with the historic ones, complicate the direct application of modern protection and rehabilitation technologies and materials to historic buildings. This is further intensified due to the accumulation of a higher environmental impact throughout time.

4. The project of the rehabilitation of the Holy Aedicule as a pilot multispectral, multidimensional, novel approach through transdisciplinarity and cooperation

Innovative scientific methodologies and challenging projects mark future trends in the protection of cultural heritage. They have initiated a universal conversation within a holistic approach, and they merge capabilities and know-how from the scientific fields of architecture, civil engineering, surveying engineering, materials science and engineering, information technology, and archaeology, as well as heritage professionals and stakeholders in cultural heritage. These methodologies and know-how can be applicable to the modern built environment, as well.

Advanced digital documentation permits the fusion of data from interdisciplinary innovative modelling, analytical and NDTs and supports the emergence of a transdisciplinary field for multispectral sustainable preservation and management of Cultural Heritage. Within the transdisciplinary field, communication, social awareness, and participation are enhanced. To this end, new funding tools, schemes, and mechanisms are searched out on the basis of reuse of heritage assets to generate revenue for a sustainable preservation towards circular economy.

The project of the rehabilitation of the Holy Aedicule of the Holy Sepulchre in Jerusalem, an emblematic monument (Biddle 1999; Corbo 1981; Coüasnon 1974; Lavas 2009; Mitropoulos 2009), of international and religious importance, is considered a pilot multispectral, multidimensional, novel approach based on transdisciplinarity and cooperation. It The project required crucial rehabilitation works to ensure its structural integrity, its sustainability and the preservation of the values it represents to the Christian community and World Heritage.

The project *"Conservation, reinforcement and repair interventions for the rehabilitation of the Holy Aedicule"* was initiated, became possible and was executed under the governance of His Beatitude, the Greek-Orthodox Patriarch of Jerusalem, Theophilos III. His Beatitude, the Greek-Orthodox Patriarch of Jerusalem, Theophilos III invited Professor Antonia Moropoulou (March 2015) and signed a programme agreement with the National Technical University of Athens (NTUA) in order to conduct a study regarding *"Materials & Conservation, Reinforcement and Rehabilitation Interventions in the Holy Edicule of the Holy Sepulchre"* with the consensus of all three Christian Communities. Following the analysis and evaluation of the results of the NTUA interdisciplinary team study (Holy Aedicule Project 2015–2016), a historic common agreement was signed in 2016, by the three Christian Communities, Guardians of the Holy Tomb, entrusting the NTUA inter-disciplinary team with the implementation of the rehabilitation project (Holy Aedicule Project 2016–2017).

4.1. Addressing the challenges of the rehabilitation project

Every preservation or rehabilitation project has its own unique challenges, in addition to the anticipated ones.

It is crucial to identify all these challenges as early as possible in the project, in order to select and employ the optimum means, scientific tools, and engineering solutions to address them as effectively as possible.

The exemplary project of the Holy Aedicule rehabilitation (Holy Aedicule Project 2016–2017) demonstrated that the optimal approach to effectively address the challenges, was through the development and implementation of *Innovation*. Two main categories of challenges were identified:

- Scientific coordination and supervision challenges
- Scientific and technical challenges

4.1.1. The scientific coordination and supervision challenges of the Holy Aedicule rehabilitation

Specifically, although, in terms of size, the Holy Aedicule might not be considered a complex large-scale rehabilitation project, it is the combination of utmost religious importance and lack of documentation suitable and relevant to the necessary works that created a wide range of scientific coordination and supervision challenges. These needed to be addressed effectively while respecting the character and the values of the monument. A similar situation can occur in most projects regarding cultural heritage assets, due to the importance of built cultural heritage (which creates scientific coordination challenges) and the "less flexible" response of the typical authorities involved (e.g. Ministries of Culture, local stakeholders, etc.). However, similar challenges may even arise in corresponding projects for modern buildings and infrastructure, due to other factors, such as even more stringent timeframes, a wider range of involved authorities (e.g. significant overlapping responsibility from various Ministries) and the need to supervise large technical teams working concurrently.

In the emblematic project of the Holy Aedicule rehabilitation, one such challenge was the coordination of an interdisciplinary team at the highest level of technical responsibility. The team had to respect the Status Quo and the three Christian communities. It had to operate within a changing environment (sensitive political and religious issues, evolving space restrictions within the Church complex, climatic variations, etc.) and within a strict timeframe (project started right after Easter 2016 and had to be completed before Easter 2017). It had to address the prerequisite that the works allowed continuous pilgrimage and religious functions, while preserving the values of the monument. Moreover, the management of all arising issues was required to be accomplished through a dynamic decision-making process, based on clear scientific support. In addition, the interdisciplinary team faced the challenge to provide scientific support to the integrated governance, during all phases of the project and within a very limited timeframe, which correspondingly required quick but accurate and thorough scientific assessments and proposals. Another related challenge was the coordination of a diverse group of people, which included the interdisciplinary NTUA team and the supporting scientists (more than 50 architects, civil/survey and rural/chemical engineers, archaeologists, and others) and the Greek teams of conservators and restorers (12 members). This diverse group was working simultaneously in two locations, locally at the worksite in Israel and at the NTUA laboratories in Greece, further complicating coordination and logistics. Furthermore, this integrated coordination of this complex project was accomplished in the sensitive environment of the open city of Jerusalem, a city of two different people and three different religions.

4.1.2. The scientific and technical challenges of the Holy Aedicule rehabilitation

In order to implement successfully the rehabilitation of the Holy Aedicule, an array of scientific and technical challenges were identified (Holy Aedicule Project 2015–2016) and addressed during the project (Holy Aedicule Project 2016–2017), that were linked to the actual works and the surrounding environment of the monument. One such challenge related to ensuring the structural integrity of the Aedicule structure. In addition to the actual works conducted on the structure and internal masonry, additional lateral supports and specially designed movable frames were designed and constructed to ensure structural integrity during the works. Another scientific and technical challenge was the design and efficient application of compatible and performing restoration materials and interventions that were required to withstand a demanding combination of thermohygric, dynamic and environmental stresses. These materials and interventions, in turn, necessitated a continuous assessment of their effectiveness and the improvement they inferred to the sustainability of the monument, as well the development of a novel multidisciplinary documentation scheme that utilized digital technologies and non-destructive testing. Furthermore, it should be noted, that since the Holy Aedicule was a largely non-documented monument (in contrast with the Church of the Resurrection within which it is located), the adopted documentation scheme allowed archiving, analysis and interpretation of the findings throughout the project (e.g. opening of the Tomb), highlighting the values of the Holy Aedicule.

4.2. Setting the goals of the project to preserve the Holy Aedicule

The goals of the project were the following: (i) addressing the critical deformations observed on the Aedicule structure, as well improving and reinstating the Aedicule's performance and structural integrity, through the use of compatible and performing materials and conservation, reinforcement and rehabilitation interventions; (ii) preservation and highlighting of the values of the Holy Aedicule; (iii) ensuring sustainability of the Holy Aedicule and the rehabilitation works, through monitoring and control of the thermohygric behavior of monument (Alexakis et al. 2018; Moropoulou et al. 2019b, 2017c). This array of goals largely dictated the approach adopted.

4.3. Main tools for the successful implementation of the Holy Aedicule rehabilitation

4.3.1. The evolution of dynamic interdisciplinary digital documentation as an integrated core space

As mentioned above, built cultural heritage, compared to the modern built environment, arguably lacks in the level of technical documentation available, i.e. documentation that can be readily utilized to design and implement required interventions. Obviously, certain scientific fields exist, e.g. archaeology or history, where documentation data are extensive, but such information is not often directly utilizable in engineering fields. In the case of modern buildings, there is a higher level of technical documentation, however, the evolution of engineering may in the future demand documentation of data, currently not envisioned.

Therefore, the first engineering stage is the provision of geometric documentation data, upon which all other analytical and non-destructive data can associate and refer to. The project of the Holy Aedicule rehabilitation benefited from recent developments in documentation, employing and fusing data from state-of-the-art instrumentation and modeling technologies in order to successfully evolve typical documentation into a dynamic digital tool that functioned as an integrated core space for the needs of the project.

Despite its importance, the Holy Aedicule of the Holy Sepulchre is a largely undocumented structure. Earlier attempts have provided information about its architecture and geometry (Biddle 1999; Corbo 1981; Coüasnon 1974; Lampropoulos, Korres, and Moropoulou 2019), but such information was neither readily available or usable for the needs of the project. The interdisciplinary team had, early in the design process, identified the need for the development of an accurate, detailed, appropriately geo-referenced geometric model of the structure. The products of this model were used for the development of interoperable detailed and representative three-dimensional structural models of the current state. Within this framework, five main documentation processes were identified and successfully applied.

4.3.1.1. Geometric documentation. A detailed geometric documentation of the Holy Aedicule was achieved, using an integrated array of geomatic techniques and geodetic instrumentation (Georgopoulos et al. 2019), such as an automated 3D imaging methodology based on high-resolution digital images, terrestrial laser scanning, and high-accuracy geodetic stations. It involved the orthogonal projection of a purposely selected set of points on horizontal or vertical planes, to record all geometric properties of the monument. These points were selected based on products' requirements set by the interdisciplinary team, to support the project throughout all stages of the project (Moropoulou et al. 2017c). Such products included high-resolution three-dimensional models of the Holy Aedicule, highly accurate geodetic measurements, conventional 2D-base material, and sections at specific locations. All products and data were georeferenced to a local plane projection reference system from a past NTUA survey (Balodimos, Lavvas, and Georgopoulos 2003).

4.3.1.2. Non-destructive prospection of the Holy Aedicule. In conjunction with the geometric documentation, a non-destructive prospection of the internal structure of the Holy Aedicule was accomplished. This prospection provided crucial information regarding the structure's internal layers and the presence of layers from previous construction phases, that was hitherto not documented. Specifically, Ground-penetrating radar (GPR) was utilized (Lampropoulos, Moropoulou, and Korres 2017) and the 2D/3D analysis of data from the survey at the exterior and interior surfaces of the Holy Aedicule revealed the presence of remnants of the original monolithic Aedicule, embedded within the current Aedicule structure. This important finding was of great importance as it proved (and subsequently was verified during the works), that the Holy Aedicule contained remnants of its previous construction phases, a theory which was based, until then, only on theoretic assumptions. The combination of the geometric model and the GPR prospection results, effectively transformed the 3D geometric model into an integrated 3D information model of the Holy Aedicule, incorporating, and thus providing, information regarding the interior of the structure (Agrafiotis et al. 2017). This can serve as a valuable tool for related historic and architectural analyses. In particular, GPR revealed and mapped the internal layers, which, in combination with geometric documentation, supported the design of the work stages and the necessary interventions, as well as quantification of the required restoration materials. Non-destructive prospection continued, throughout the works, complementing initial data with additional data from all stages (Alexakis et al. 2018).

4.3.1.3. Interdisciplinary digital documentation. It refers to the acquisition and cross-utilization of data provided from an array of complementary analytical and non-destructive techniques (Alexakis et al. 2018; Apostolopoulou et al. 2017, 2018; Moropoulou et al. 2017a) and its digitalization. Emphasis was given on obtaining and analysing information within digital formats, and, furthermore, geo-referenced, wherever feasible. By actively adopting the digital documentation approach, throughout all stages of the Holy Aedicule rehabilitation project, enhanced digital documentation products were developed (Georgopoulos et al. 2017; Moropoulou et al. 2017b), at two levels:

(i) geometric information enriched with prospection data,

(ii) information regarding the state of preservation of the Holy Aedicule, deriving from non-destructive techniques (e.g. infra-red thermography, high-resolution digital imaging, terrestrial laser scanning, endoscopy, microscopy, etc.) and/or materials characterization data (e.g. thermal analysis, microstructural analyses, etc.).

The joint digital integration of multi-spectral information, enabled the cross-enhancement of the digital products, from all involved documentation techniques, thus providing an improved knowledge of the building, supporting all activities throughout the project (Alexakis et al. 2018).

4.3.1.4. The fusion of geometric, architectural, materials and structural information. As mentioned above, throughout the Holy Aedicule rehabilitation project, the fragmented approach was decisively abandoned, due to its inefficiency. Instead an integrated approach was adopted. This proved critical for the assessment of the state of the bearing structure, prior to the selection and design of the appropriate restoration actions. The availability of optimized and enhanced information from the correlation of geometric, architectural, materials characterization and prospection analyses, enabled the development, validation and successful application of an optimized assessment process (Spyrakos, Maniatakis, and Moropoulou 2019). Thus, the Holy Aedicule was examined under both static and seismic loads via comprehensive finite element modelling and structural analysis (Figure 1) taking into account all the aforementioned data. This optimized assessment process assisted in identifying the critical areas of the Holy Aedicule requiring interventions. Furthermore, different restoration scenarios (regarding restoration materials and interventions) were assessed through modified finite element model analysis, in order to select the

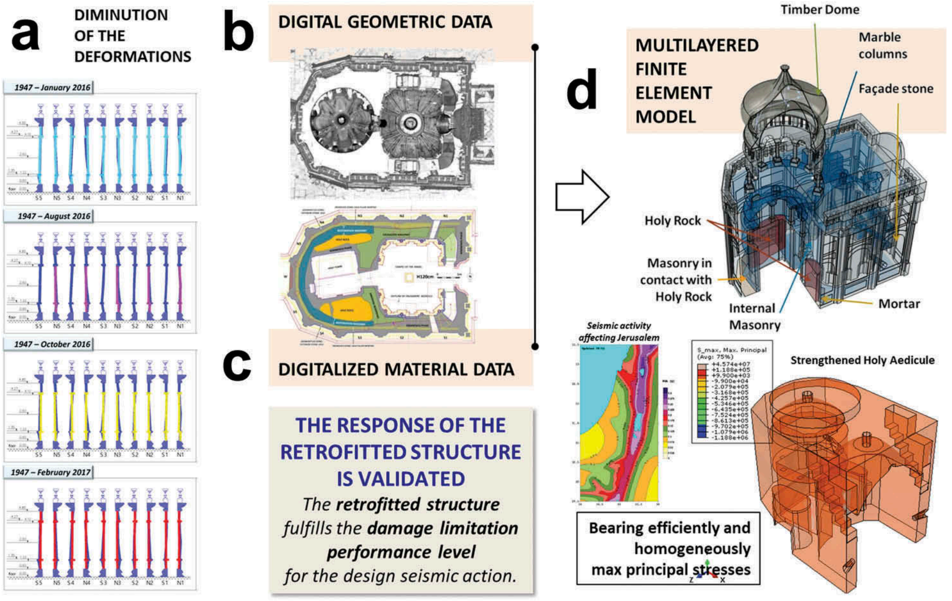

Figure 1. Fusion of geometric, architectural, materials and structural information in the project of the Holy Aedicule rehabilitation.

optimum, prior to the project. After the project initiated, subsequent assessment models were developed, introducing all the remedying measures employed during the works, as well as additional non-destructive, geometric and other documentation data that emerged during the project. As such, close cooperation of all related fields was achieved, in practise and throughout the duration of the works, fusing all relevant non-destructive and analytical capabilities towards the achievement of an augmented assessment capacity of the Holy Aedicule project. This process, not only guided the restoration action and selection of materials, assuring structural integrity throughout the project, but also validated the assurance of structural integrity upon the completion of the project, through the integration of all relevant data of the final state of the monument.

4.3.1.5. Knowledge-based digital infrastructure to support the design and validation of the rehabilitation interventions throughout the project. The aforementioned integrated digital documentation and analysis approach provided an array of advantages. It enabled the interdisciplinary Team and the supporting scientific members, to design, validate, optimize and implement the selected rehabilitation materials and interventions assisted by a knowledge-based digital infrastructure environment. As aforementioned, this process prior to the initiation of the works, proved as a very valuable tool for ensuring the soundness and effectiveness of the selected solutions. The main engineering goal of addressing the critical deformations of the Aedicule structure and the improvement and reinstatement of the Aedicule's performance and structural integrity, was assessed by introducing the selected compatible and performing materials and conservation, reinforcement and rehabilitation interventions into the aforementioned optimized finite element model and validating the effectiveness of the selected remedying measures (ASCE). This digital infrastructure had the added advantage of allowing minor adaptations of the selected measures, based on a prompt assessment response from the optimized model, whenever new findings, upon implementation of the works, dictated alteration of the designed solutions. Thus, materials and interventions could be slightly adapted in order to achieve the optimum results.

4.3.2. *Optimization of planning of all stages of the rehabilitation works while addressing case-specific limitations*

It is typical for complex engineering projects to employ comprehensive planning of all stages in order to (i) minimize cost, (ii) reduce the required duration of the project and (iii) improve the utilization of human and technical resources. Such planning processes are supported by relevant software and expert experience. Planning, however, is generally more difficult in projects involving historic buildings, since usually, additional requirements are typically set, due to the importance of the asset. Therefore, planning approaches that are generally applicable to modern structures require case-by-case adaptation in the case of historic buildings. As mentioned above, in the case of the Holy Aedicule rehabilitation, a rather strict set of requirements existed:

- The Holy Aedicule should continue be accessible to the Three Christian Communities for religious functions, as well as for pilgrimage;
- Timeframe of completion was strict and non-extendable (less than 12 months);
- Space for the setup of the worksite was limited; furthermore, the worksite was required to be set-up in such a manner, as to not obstruct the church's functions;
- Above all, the values of the monument were to be respected and highlighted.

Within this demanding framework of requirements, all stages of the works and logistics of human resources, instrumentation, and materials were carefully planned and controlled, so that necessary works could be performed in parallel at adjacent areas of the Aedicule. Furthermore, the two main laboratories were set-up within the Church of the Holy Sepulchre, i.e. the Cleaning and Protection Laboratory and the Interdisciplinary Monitoring and Documentation Laboratory, while research and planning activities were also conducted at the NTUA facilities (mainly scientific and analytical activities). It should be noted that the set-up of the two on-site laboratories was not a trivial task, as their scientific and technical equipment was gradually procured after the initiation of the works, necessitating the utilization of equivalent equipment and resources from NTUA, which was transferred locally until the two laboratories were in a position to function in full capacity. It should also be pointed out that the aforementioned digital documentation and knowledge-based digital infrastructure, provided further flexibility to the planning process. This was especially important whenever deviations from the scheduled tasks were required, due to unforeseen factors. This framework provided feed-back and ensured prompt assessment of the effectiveness of the adjusted solutions.

In order to address the project's requirements, the following main stages were planned and successfully completed (Holy Aedicule Project 2016–2017; Moropoulou 2017a; Moropoulou et al. 2017c, 2019c):

- Provide additional support to the Aedicule's existing metal frame;
- Dismantle and remove the stone panels, starting from the northeast façade (N1) and working westwards and circular;
- Remove the disintegrated and incompatible mortars from the revealed masonry;
- Repoint the historic masonry, as well as repair and partially reconstruct a part of the masonry in need of strengthening;
- Inject grouts up to 3 m;
- Reset and anchor the exterior columns;
- Reassemble the stone panels, while applying a compatible concrete-type restoration filling material between the masonry and the reassembled stones;
- Reset and anchor the stone column railing;
- Complete grouting of top zone and terrace;
- Anchor the interior marbles;
- Implement the required conservation interventions on the Onion Dome, on the Dome of the Chapel of the Angel and on the Dome of the Burial Chamber;
- Apply final mortar, pointing and finishing;
- Implement cleaning and protection works of interior and exterior architectural surfaces and decorative elements.

The actual works were performed during the night, when the Church was closed to the public, with the exception of the 60 h when the Tomb of Christ was opened, during the grouting process, when the monument was inaccessible to the public.

4.3.3. Scientific support to the integrated governance of the project

It is generally accepted that the provision of scientific support to projects for the protection, preservation, and rehabilitation of built-environment offers invaluable advantages, while ensuring that critical mistakes of the past are avoided. In historic building applications, different schemes of governance are utilized; the greater role of the authorities must be taken into consideration, thus diverging from purely technical projects. In the case of the Holy Aedicule rehabilitation, in particular, the role and influence of the three Christian Communities, was critical. The cooperation of Religion and Science was successfully attained through the integrated governance (Moropoulou and Moropoulos 2019), with the responsibility of the three Christian communities and the scientific supervision and monitoring of the NTUA interdisciplinary team.

The cooperation of Science and Religion relied on the intersection of the different disciplines, involved in the project, and the multi-interface interactions between the scientific teams, the workers, the Common Technical Bureau of the Church of the Holy Sepulchre and the three Christian communities, all under the authority of His Beatitude, Theophilos III. The statutory framework for the implementation of the project was provided by the *Common Agreement*, signed by the three Christian Communities, ensuring respect to the Status Quo of the three Christian communities, Guardians of the Holy Tomb.

The project was implemented under an integrated governance, comprising of the Project Owners Committee and the Steering Committee, adjoining the scientific and the technical directors of the project. It was achieved on the basis of the NTUA study (Holy Aedicule Project 2015–2016), and ensured through the NTUA scientific reports (Moropoulou 2016–2017) throughout the implementation of the study. Through this integrated governance, the diverse team of scientists, workers, conservators, researchers, practitioners, heritage professionals, policymakers, worked together, within a transdisciplinary context (Moropoulou et al. 2018a). Thus, not only were the project's goals successfully achieved, but, this synergy also resulted in a conscious shifting of the academic and technical communities from the technical/scientific rationality towards an epistemic culture. Within this, none of the scientific disciplines involved in the project prevailed over the others, but all cooperated with, and benefited from, the achievements of each other. This attitude, in turn, enhanced the credibility of the provided scientific support to the integrated governance of the project (Moropoulou et al. 2016a, 2016b).

The project of the Holy Aedicule successfully demonstrated the validity and advantages of future trends in the protection of cultural heritage, applicable also to modern built environment, where the close cooperation between all scientists, technical communities, authorities and stakeholders and the elimination of "boundaries" are vital prerequisites for the successful completion of such projects.

4.4. Achievement of the project goals

4.4.1. Ensure the structural integrity of the Holy Aedicule

As mentioned above, one of the main goals of the project was to address the critical deformations observed on the Aedicule structure, as well as to improve and reinstate the Aedicule's performance and structural integrity. Already, as aforementioned, through the NTUA interdisciplinary diagnostic study (Holy Aedicule Project 2015–2016), compatible and performing materials and conservation, reinforcement and rehabilitation interventions were selected for the project, to achieve this goal.

A detailed description of the relevant stages of the technical works that were implemented to ensure the structural integrity of the Aedicule has been presented elsewhere (Moropoulou et al. 2017a, 2017c, 2018c, 2019c). Nonetheless, for the scope of this work, the Holy Aedicule project can offer the main elements of the methodological perspective for the selection and implementation of these activities, in order to serve as a paradigm for other cases, especially regarding readjustment actions.

4.4.1.1. Extent of dismantling and partial reconstruction of the structure. One of the basic decisions regarded the extent of dismantling and reconstruction. In contemporary and modern buildings, this is dictated by cost-related issues and can have a wide range (from minor modifications to complete demolition and reconstruction). In the case of listed buildings of historic and architectural significance, this matter is generally addressed in a less aggressive approach, for example, retention only of the cell of a building, on account of its architectural value. As the cultural heritage value of an asset increases, as much of the original structure is required to be preserved, albeit modified to feasibly conform to current standards and requirements.

In the case of important monuments and historic structures, this issue is obviously of utmost importance. The extent of dismantling and reconstruction is governed by the state of preservation of the structure, on the one hand, and the importance of the structure on the other. These two, sometimes rivalling, matters, must compromise towards the optimum solution, in order to achieve durability and proper response of the structure. There is a tendency to often focus on specific parts of a structure and decide on the extent of their dismantling and reconstruction, without taking into account their impact on the whole structure. Instead, the structure should be studied as a whole and avoid fragmented decisions.

The Holy Aedicule, a multi-layered structure, contains "layers of history", demanding their preservation to the highest extent possible. However, the severe deformations it presented, demanded access to the internal layers of the structure, to address the problems. Thus, the dismantling of the exterior stone facades, enveloping the structure, was considered a necessity, in order to provide access to the damaged internal masonry. However, aiming to minimize interventions, it was decided to only dismantle the stone slabs necessary to provide access to critical areas. In order to ensure the preservation of the structure, the dismantling process followed a very strict and organized procedure, fully documenting each stone slab of the façade, in order to ensure its correct reposition after strengthening the interior layers.

After the masonry was accessible and could be assessed in situ, it was verified that parts of the masonry were in an extremely bad state of preservation. Integration of this new information in the model, revealed that the masonry required additional strengthening measures. Thus, scientific support to decision-making dictated, in practice and real-time, the readjustment of the planned masonry strengthening interventions.

In particular, the lower parts of the historic masonry around the Tomb Chamber, presented severe damage and posed not only a threat to the structural integrity of the Holy Aedicule, but also to the Holy Rock embedded within the masonry. Thus, despite the historic masonry's importance, it was decided that these parts were to be reconstructed, using the same lithotype. Furthermore, these parts were constructed in such a manner, as to conform to the curvature of the Holy Rock, relieving it from vertical loads and ensuring its preservation. Thus, the value of the masonry was preserved to the highest extent possible, in terms of material provenance, the Holy Rock was protected, and the integrity of the structure was achieved.

This is a prime example where engineering decisions need to be made based on interdisciplinary scientific data, that require a fine balance between preservation of values and the achievement of engineering goals.

This approach highlighted the value of a comprehensive diagnostic study, that can provide scientific support to decisions relating to (i) the extent of dismantling, (ii) the necessity of reconstruction and (iii) the type and organization of rehabilitation works. This is applicable to modern buildings as well, where, however, the importance of cost and performance prevails.

4.4.1.2. Strengthening the structure. In the framework of enhancing the sustainability of the structure, the NTUA interdisciplinary team substantiated to the integrated Governance the combined need to homogenize the masonry (as it consisted of many construction phases and layers) and consolidate the embedded remnants of the original Aedicule (the Holy Rock, i.e. the original Tomb), through the application of a compatible and performing grout, already selected during the diagnostic study. Although this is a typical step in cases involving historic buildings, and rather common in modern buildings, in the case of the Holy Aedicule it was an important decision, as it involved the opening of the Tomb, after centuries, in order to protect it during the grouting process. This highlights the importance of taking issues, other than purely technical ones, into account, in order to address structural issues, while preserving the values. Although these measures may pose additional technical limitations, they are necessary in order to protect the values of the building or infrastructure. Moreover, in the case of the Holy Aedicule, the grouting process was carefully designed, executed and documented. It involved the design of a grout insertion tube matrix that was based on digital geometric data, non-destructive prospection with GPR and materials data. Furthermore, findings from the structural analysis of the Aedicule, regarding critical areas, dictated the planning. The grouting process was monitored throughout the duration, digitally documented and multispectrally assessed for its effectiveness. This fusion of data provided new information regarding the internal layers of the Aedicule and its construction phases. This dictated the necessity of grouting the upper zone of the Aedicule (above 3 m, i.e. above the opened panels), which was not initially planned; thus, it is obvious how integration of multispectral data can assist in the readjustment of preplanned actions (Alexakis et al. 2018).

Thus, the importance of documenting such critical interventions emerges, for documentation, assessment and monitoring purposes, while it can also serve for future reference for preventive maintenance. Documentation of grouting and monitoring of the process through non-destructive testing, within a holistic scheme, and integration of this information in a model, are important for modern buildings and infrastructures as well. This should be taken into account in BIM systems, as it can also serve for readjustments during the process, increasing the effectiveness of the procedure.

4.4.1.3. Diminishing deformations and monitoring during the restoration works. Monitoring the deformations of the Holy Aedicule was a very important task, implemented continuously throughout the restoration interventions. In addition to strengthening the masonry, the dislocated columns and the exterior panels were reset, which was a necessary and crucial step towards the diminution of the deformations. Data from the monitoring of this process, were used to ensure that the diminution of the structure achieved the optimum level. These data were integrated into the model of the Holy Aedicule in order to evaluate structural integrity at all times.

Additional structural integrity-related measures included the anchoring of the reset columns to the strengthened masonry using specially ribbed grade 2 titanium bars, a material that was selected due to its durability and performance. It should be noted that the effectiveness of the anchor systems (titanium bars and mortars) were tested in lab and in-situ. Testing, using the same materials as the structure, is extremely important to ensure that engineering solutions are based on real-time and real-scale experiments, such as in situ pull-out tests. In the case of the Holy Aedicule, the non-visibility of the anchors was an important issue, and necessitated a series of tests to examine which was the most aesthetically appropriate manner to conceal them (Moropoulou et al. 2017c), thus addressing issues relating to the historic importance of the monument, while ensuring structural integrity.

4.4.1.4. Reassembling process. A titanium mesh was also installed between the strengthened masonry and the reset panels, to enhance the bond of the successive concrete layers, upon which the external stone panels were gradually — per height — reassembled in their reset position. Similarly, each reassembled stone slab was anchored to the masonry and to adjacent units with titanium bars and connectors. It should be underlined that the location of each titanium connector was carefully designed and validated (through the study of the simulated response of the retrofitted structure by finite element modeling) to improve the dynamic performance of the panels against seismic actions, and digitally documented for future studies. Next, a compatible and performing restoration concrete-type material was applied in the gap between the anchored external stone slabs and the reinforced masonry (Apostolopoulou et al. 2018), until the panels were fully reassembled. Documentation during the previous phases of the project was crucial for the successful and accurate reassembly.

4.4.1.5. Assessment of the implemented measures. Following the completion of the strengthening activities, all of which were fully digitally documented, as mentioned above, the retrofitted and strengthened structure was evaluated in its final state. It utilized the updated geometric data (incorporating the diminution of deformations), and the updated finite element model (incorporating the restoration materials, reconstructed parts, titanium anchors and connectors). This integrated model, through this fusion of information, confirmed that the structural integrity of the Holy Aedicule was attained (Spyrakos, Maniatakis, and Moropoulou 2019). This demonstrates the importance of exploiting integrated models, to support crucial assessments in projects. Thus, with structural integrity ensured, the iron frame installed by the British Mandate, as well as the additional lateral supports, were removed, "freeing" the monument of its "iron cage" after almost 70 years.

4.4.1.6. Scientific support as the basis of optimization processes and selection of optimum materials. As illustrated in the above subsections, scientific support is also crucial for readjustment issues, thus optimizing restoration actions to achieve a project's engineering goals. The Holy Aedicule project highlighted the need for scientific support to the design and digital documentation, even for phenomenally trivial tasks, such as anchoring of structural elements or designing the positions of grout insertion points. This is important in historic building applications, where the modifications to the original structure need to be minimized. It also highlighted the benefits of state-of-the-art materials (e.g. titanium bars, modern restoration mortars) in inferring a considerable improvement in the performance of a structure, with the least degree of intervention, and while respecting and preserving its values. It should be noted that in the case of emblematic monuments, such as the Holy Aedicule, sustainability issues prevail over cost concerns. However, in other cases, where the value of the asset does not justify the optimum and most performing engineering solutions, an optimization must be achieved, between cost, performance, and sustainability.

The Holy Aedicule project, thus, serves as a prime example where scientific findings combined with integrated analysis can provide focused interventions with a multitude of beneficial effects, addressing both technical issues and historical concerns.

4.4.2. Reveal and interpret findings to preserve and highlight the values of the Holy Aedicule

As discussed above, projects involving the protection, preservation, and rehabilitation of built cultural heritage often rely on a less extensive level of documentation relevant to the technical needs of the projects, as compared to modern building applications. As a result, however, such projects offer the opportunity to satisfy the needs and complement existing knowledge of closely related scientific fields, such as archaeology, history, etc.

In the case of the Holy Aedicule rehabilitation project, the findings from the diagnostic study, such as the non-destructive prospection of the structure which revealed the hidden layers of the Aedicule and the presence of remnants of the original Aedicule embedded within the current structure, revealed new information about the monument that was until the project unknown or only theorized (Lampropoulos, Moropoulou, and Korres 2017). The NTUA diagnostic study, as well as the documentation and monitoring of the works during the various stages of the project revealed and highlighted the "continuity" of the monument and its evolution throughout the centuries (Lampropoulos, Korres, and Moropoulou 2019). Analysis validated that it is a rather complex structure, encompassing parts from various construction periods, with a large variety of building materials and traces of anthropogenic and natural impact on the structure. Besides the technical merits of such information (Moropoulou et al. 2017c), it is of even more significant value for archaeologists and historians,, as, for example, archaeometry can scientifically direct historic interpretation and architectural analysis (Moropoulou et al. 2018b), while material provenance can reveal information regarding trading routes (Moropoulou et al. 2019a). Of course, this information, is of even greater importance and value, when linked to the geometry of the structure (Moropoulou et al. 2017b), at the same time enhancing digital documentation of the project for further study of the monument (Georgopoulos et al. 2017). Such information, is thus provided to other researchers, through scientific publications, scientific presentations in Conferences, organized in a wide range of disciplines internationally (e.g. Moropoulou 2017b, 2017c; Moropoulou 2016a, 2016b, 2018a), but also through a digital information depository (Alexakis et al. 2019). Social accessibility of this information to the wider public and scientific community (Moropoulou et al. 2018a) is further enhanced by the organization of specialized exhibitions,[1] as well as public presentations (Moropoulou 2018b). This multi-leveled diffusion approach, should be adopted for similar cases, both for historic and contemporary buildings, aiming to advance scientific knowledge and, at the same time, inform and educate the general public.

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[1] *Tomb of Christ. An interactive exhibition*. National Geographic Museum, Washington DC, November 15, 2017 — January 1, 2019. *The Tomb of Christ*. The monument and the project. Digital exhibition of advanced technology. Byzantine and Christian Museum, Athens, Greece. May 21, 2018 — January 31, 2019.

One such emblematic finding of utmost importance was the revealing of the morphology of the Holy Tomb. The Tomb was opened, as part of the aforementioned strengthening activities, after almost five centuries. The scientific team had the opportunity to document and analyze the Tomb's morphology and materials, revealing exciting scientific information which verified that this Tomb is, in fact, the same one identified by Constantine and Helena as the Tomb of Christ (Moropoulou et al. 2019a, 2018b). In conjunction with architectural and structural analyses (Lampropoulos, Korres, and Moropoulou 2019; Lampropoulos, Moropoulou, and Korres 2017), it was confirmed that the Holy Aedicule was never reconstructed from its foundations, as many have claimed (Biddle 1999; Mitropoulos 2009) in the past (major reconstructions: Bonifaccio da Ragusa-1555, Komnenos-1810), but instead gradually evolved structurally and functionally through the centuries by embedding remnants of the previous constructions phases (Lampropoulos, Korres, and Moropoulou 2019; Moropoulou et al. 2018b).

The paradigm of the Holy Aedicule highlights the benefits of Transdisciplinarity and Cooperation in the protection of built cultural heritage. It also emphasizes the close interaction of Science with Culture. Science needs to provide feasible solutions to preserve the values of our built heritage, whereas, Culture provides the knowledge from the past and additional challenges for Science to address and, thus, evolve. The new scientific capacity which emerged is now readily applicable to other historic buildings and to modern structures and infrastructures, by adaptation of the developed methodology and technological capabilities of the Holy Aedicule rehabilitation project.

4.4.3. Addressing sustainability

The preservation of modern and historic buildings and infrastructure, in variable environments and risk conditions, is not limited to implementing measures that will reinstate the state of preservation and integrity of a building or a structure. Nowadays, the issue of sustainability arises as a major design factor in preservation projects. This issue has emerged due to the realization that it is not effective to simply address damage and impact sustained to the buildings and infrastructures in the past. To the contrary, it is necessary to ensure that these retrofitted and rehabilitated structures are sufficiently resilient to variable environments and risk conditions, and to the ever-increasing threats from climate change. In order to achieve sustainability, two additional nodes of activities are typically associated with preservation and rehabilitation projects: (i)lateral activities that minimize or diminish the risks to sustainability; (ii) monitoring of the response of the building or infrastructure.

In the case of the Holy Aedicule rehabilitation, the actions proposed to minimize or diminish the risks to sustainability focused on the critical role of rising damp and moisture transfer within and around the Aedicule, as revealed by the interdisciplinary NTUA diagnostic study (Holy Aedicule Project 2015–2016). As part of the actual works, a comprehensive 3D non-destructive prospection and geometric documentation of the underground environment of the Holy Aedicule and its surrounding environment (the Rotunda area and the adjacent areas within the Church of the Holy Sepulchre), revealed a complex underground morphology. A cluster of underground features were revealed, either natural or man-made — often interconnected with each other. Additionally, a multitude of partially documented water-drainage and sewage networks were examined and found in a poor state of preservation. Examination of the foundations, revealed the negative impact of this complex underground environment, which poses a risk to the sustainability of the Holy Aedicule and the implemented rehabilitation works, as assessed by a relevant preliminary study (Holy Aedicule Project 2016–2017). This study demonstrated (through geophysical study and numerical analysis) that the foundation system of the Aedicule is at risk, since the bedrock level of the quarry area, below and around the Aedicule, is strongly irregular, and that the Aedicule foundations lie on a degraded thin bedding layer of low silicate mortar or rubble of older structures that are not sufficiently consolidated. As a result of this situation, a differential settlement of the structure is observed, due to long-term reduction in the rubble's stiffness.

The NTUA interdisciplinary team proposed a novel underground intervention. A peripheral drainage and ventilation gallery was proposed to be excavated around the Holy Aedicule, covered and not visible from the pilgrims at the Rotunda ground level. This excavation will provide direct access to the foundations of the Aedicule, which will be strengthened and reconstructed as needed. Interventions also involve grouting of the rubble and/or removing it and replacing it with compatible and performing mortar and stonework (Holy Aedicule Project 2016–2017). Thus, the differential settlement of the structure will be addressed directly. In addition, a built-in system of open canals, pipes and pumps, within the space between the gallery and the natural bedrock, will also allow drainage of the rising underground water. A co-located ventilating system will be integrated within this gallery, for the optimization of aeration and humidity regulation of the gallery, the Aedicule's foundations. This ventilation system will also address humidity issues of the adjacent underground areas, such as the Hadrian cistern north of the Aedicule, and the earlier excavation site south of the Aedicule (over which a glass floor will be installed to allow visitors to observe the excavation site and the archaeological findings within this area). A remote-controlled multi-sensor system will monitor humidity uptake in the Aedicule's vicinity. Additionally, a new functional sewage and rainwater network is proposed to be constructed, within the perimeter of the Rotunda and in the Church of the Holy Sepulchre, to replace the complex and currently ineffective existing network.

The construction of this peripheral gallery demonstrates the flexibility of modern "smart" solutions. The proposed installation of a glass floor over the Corbo excavation area (Corbo 1981), at the south part of the Rotunda, preserves the archaeological values of the monument and highlights the continuity of the Aedicule throughout the centuries. The paradigm of the Holy Aedicule rehabilitation project, therefore, emphasizes the benefits of similar "smart" multi-functional interventions, which should be the trend in the protection of built cultural heritage as well as for modern buildings and infrastructure applications. It also underlines the importance of taking into account the environment of a structure/infrastructure, in a beneficial approach, by actively adjusting it.

The second node of activities involve monitoring the response of the building or infrastructure. Although the actual rehabilitation works ensured the sustainability of the Aedicule, it is important to monitor critical risks, within an integrated cultural heritage management approach, in order to be able to assess the impact of the "total environment" on the rehabilitated Aedicule structure. Within this framework, and as part of the rehabilitation project, a climatic monitoring and control system was designed and installed. It comprises of a wireless sensor system that monitors the microclimatic conditions (air temperature and relative humidity). Sensors were installed at various critical locations within the Tomb chamber and the Chapel of the Angel (Holy Aedicule Project 2016–2017). In addition, a specially designed ventilation and dehumidification system was installed at the roof of the Holy Aedicule, below the Cupola, which dynamically adjusts airflow and dehumidification levels through analysis of data acquired from the monitoring system. To complement the monitoring of the microclimatic conditions, an additional-wired sensor system for measuring materials' moisture was installed, during the works, inside the Aedicule's masonry, at selected areas of different height and orientation. This system allows us to monitor the rising damp directly at the masonry areas and to assess the thermo-hygric response of the monument, both important factors for its sustainability.

Furthermore, a structural health monitoring system was designed and installed, to achieve monitoring of the response of the Holy Aedicule, regarding earthquake stresses and spatial data. Specifically, a monitoring subsystem was installed for evaluating the structural response of the monument under seismic loads ((Holy Aedicule Project 2016–2017; Moropoulou et al. 2017c, 2019c), to monitor and assess the dynamic behavior of the Holy Aedicule. It consists of digital triaxial accelerometers installed at certain locations at the Aedicule, aiming to characterize its translational and rotational response. This subsystem can record accelerations continuously, offering remote data and real-time data acquisition capabilities. The second element of the structural health monitoring system regards spatial monitoring. An advanced total station (Trimble S9) was setup which provides static and dynamic monitoring of the Holy Aedicule's displacements. It is based on a 13-points 3D network established for the determination of the Aedicule's displacements and supports high-accuracy measurements. Measurements are conducted in wide-time intervals (weekly, monthly, annual) followed by total post-processing and dynamic monitoring, implemented at close-time intervals (hourly, etc.) followed by simpler real-time data processing. More importantly, due to the workstation's internet access, the transfer of data and results to authorized users worldwide is feasible, for further processing, documentation and scientific analysis.

The Holy Aedicule rehabilitation project highlighted the need to include such monitoring systems in the design of interventions, since after the completion of the works, some elements of such systems cannot be installed, e.g. the in-masonry wired sensors. Moreover, the availability of such systems during the early stages of the works provides crucial reference data, that are indispensable for the optimum analysis of the response of the retrofitted structure. And more importantly, such systems should operate continually, in automatic modes, and be able to transfer their data via secure links to all authorized users of such information, for further processing, analysis, and assessment of the response of the building or infrastructure. Obviously, a vital issue is the development and definition of critical threshold levels of critical parameters that will trigger appropriate maintenance actions.

4.4.4. The benefits of innovative multilayer data management

It has become apparent, from the above discussion, that complex projects for the sustainable preservation of modern and historic buildings and infrastructure "generate" an enormous amount of multi-spectral data. Nowadays, due to technological advances and capabilities these data deliver information from various-related scientific and technical disciplines (Vodopivec, Eppich, and Žarnić 2014). They span in time from prior- to post-works; furthermore, an even larger amount of data is acquired, and must be taken into account, from monitoring activities. This accumulation of data should not be considered a challenge but rather an opportunity to establish and develop transdisciplinarity among relevant scientific and engineering fields, digital and non-digital layers of information and non-destructive and analytical information creation technologies. Within this context, an *Integrated Information System Platform* emerges as an indispensable tool for engineers and stakeholders. Such a platform can exploit and support analysis of the information acquired, it can set interrelationships and it can provide a digital infrastructure, where information can be assigned spatially for further correlation.

In the case of the Holy Aedicule project, a digital management system was developed (Alexakis et al. 2019), offering modular functionalities. This system is extendable, transferable and applicable to other cases. Geo-referenced data are available for optimal archiving, retrieval and cross-discipline data analysis, for automated identification of threats and alarm triggering. This is achieved through a spatial database generated by the integrated dynamic digital documentation of the Holy Aedicule, as discussed above. It encompasses multi-layered management of information (including multi-spectral data from non-destructive/analytical techniques, spatial and time-data registration, historic documentation, and other sources) through big data integration. It enables researchers and stakeholders, from a wide range of disciplines, to register data directly on the exact location where the measurements refer to, thus supporting a holistic management scheme. The Holy Aedicule rehabilitation was an emblematic use case where the abundance of multi-layered and multispectral information was turned into an advantage for their analysis and management, through a specially designed platform. This approach is also applicable to modern and historic buildings, with appropriate modifications, while it can also assist in preventive conservation and protection, especially under variable environments and risk conditions.

5. A new holistic approach to the effective safeguarding and management of modern, historic buildings and infrastructures

As discussed above, modern and historic buildings and infrastructure are subjected to various environmental and anthropogenic factors. In addition to the degradation of their materials, structures and infrastructure are subjected to significant risks from earthquakes, floods, extreme weather, fires, etc. Climate change further aggravates the impact of such events, in some cases even their frequency and intensity.

This situation highlights the importance for preservation and maintenance approaches that address these specific risks, effectively, and in terms of sustainability. These approaches should exploit the latest technological advances, while incorporating the lessons from past experience and know-how. As such, the preservation and maintenance of our built environment should adopt a more holistic approach (Figure 2).

Specifically, in the past, traditional preservation and maintenance approaches, addressed the risks in a fragmented manner, mainly due to difficulties in acquiring, analysing, and managing large quantities of information, often from different disciplines. This approach is considered, nowadays, as having a limited effectiveness, due to the fragmented usability of this information. Instead, the trend towards transdisciplinary projects and the relevant creation of transdisciplinary knowledge is nowadays seen as the optimal approach to increase their effectiveness of works and enhance the sustainability of our built environment.

However, the creation of transdisciplinary knowledge alone cannot ensure the increase in effectiveness and sustainability unless it is combined with (i) recognizing, analysing and addressing user requirements, (ii) taking into account land use and urban planning, (iii) engaging into a multicultural dialogue and inter-scientific reliance and (iv) achieving socio-economic development. Recent advancements in semantic-oriented modelling (INCEPTION 2015–2019) enable the effective synthesis of such a diverse set of information and requirements. The adoption of a holistic, digital-driven approach can create additional benefits through (i) the active participation of an informed and engaged Society (ii) the function within an integrated governance, (iii) the implementation of projects with financial transparency and finally through (iv) a broader initiation of public–private partnerships with an emphasis on Social Economy.

Of course, the above framework can only be realized through Innovation. Dynamic Scientific Support is obviously a prerequisite to succeed in this approach,

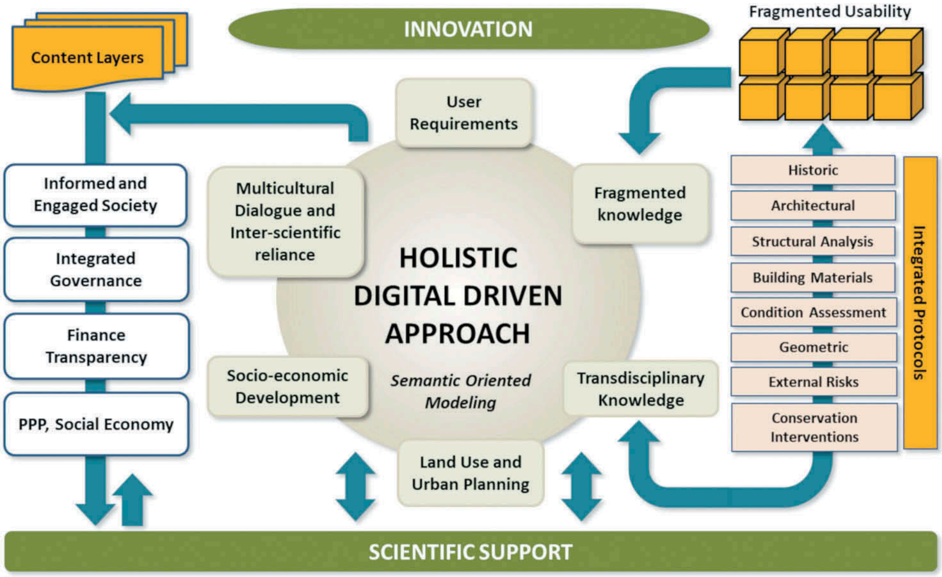

Figure 2. The concept of a Holistic digital-driven approach.

throughout the process, from data acquisition to the successful implementation of performing and effective works.

Within this framework, a methodological approach emerges regarding the development of a decision support system (Figure 3).This proposed decision support system integrates diagnosis, prediction, planning, implementation, monitoring and documentation of an asset within a dynamic iterating process. Information regarding diagnosis of the current state of the asset, is introduced into the *Resilience Integrated Model* of the asset (Doulamis et al. 2019). The Resilience Integrated Model (RIM) encompasses domain-protocols of the asset, relevant to the assets' (i) architecture and geotechnical environment, (ii) geometric knowledge, and (iii), structural performance, as well as (iv) materials characteristics. In addition, the RIM includes information regarding the natural (IPCC 2014) and anthropogenic environmental loads, such as earthquakes, floods, extreme weather phenomena, fire, etc. A set of resilience features is then defined that enables the correlation of different domain-specific attributes and reflects how these threats and risks are multiplied.

This integrated information is then combined with updated data from monitoring processes in order to identify, analyse and predict the developing risks. These

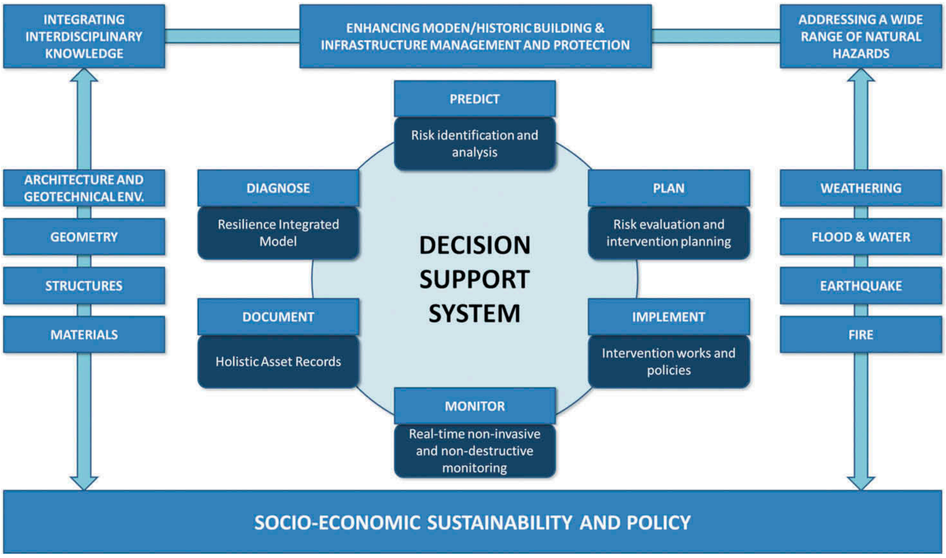

Figure 3. Main elements of a decision support system for effective safeguarding and management of modern, historic buildings and infrastructures (Doulamis et al. 2019).

risks are evaluated (IRGC 2005, 2017; UNISDR 2015), based on predetermined threshold levels, taking into account the constraints set from available financial and technological resources, thus allowing the development of an intervention strategy.

During the implementation of the selected works, the documentation of all activities permits the update of *Holistic Asset Records*. As the interventions are implemented, the knowledge base is updated by utilizing an array of real-time non-invasive and non-destructive monitoring techniques. Such efficient monitoring and documentation processes act as critical feed-back mechanisms for the continuous diagnosis and risk prediction processes, and ensure that planning and intervention strategies remain current and effective.

Such an innovative integrated Decision Support Platform can function as an intelligent, highly adaptable toolkit. Such a toolkit that enables engineers, stakeholders, and other related authorities to provide cost- and resource-effective, efficient and sustainable interventions for modern/historic buildings and infrastructures, in variable environments and risks conditions.

6. Conclusions

The necessity for an integrated methodology of diagnosis and control for the protection and conservation of modern and historic buildings and infrastructure is obvious in recent years, especially taking into account today’s aggressive environment and the increasing negative effects of climate change. This can only be achieved through innovative multidisciplinary and multispectral approaches, aided by Research.

A holistic approach is desirable for the protection and rehabilitation of both modern/contemporary and historic buildings and infrastructures. However, although modern protection and rehabilitation technologies are highly applicable on modern structures, this is not the case when dealing with historic buildings and infrastructures. The lack of crucial information, as well as the compatibility issues of modern technologies and restoration materials with the historic ones, intensify the demand for a holistic approach for historic buildings and infrastructures.

Such an innovative, holistic approach was adopted in the case of the Holy Aedicule rehabilitation. This approach was necessary due to the importance of the monument and managed to address the engineering, organizational and scientific challenges, while preserving the values of the monument. It was achieved by merging multispectral and multidimensional data and information, from complementing non-destructive and analytical techniques. A knowledge-based digital infrastructure was developed, allowing for the design and/or modification of the relevant models and planned interventions, based on an enhanced focus on materials, documentation and new findings, throughout the project. Thus, materials and interventions could be slightly adapted in order to achieve the optimum results, while the effectiveness of the rehabilitation interventions could be validated at all times.

The project demonstrated the necessity of post-project activities that have a beneficial impact on the sustainability of the rehabilitated structure. Within this framework, the benefits of monitoring are highlighted, allowing the implementation of remedying actions whenever triggered by external environmental effects. In the case of the Holy Aedicule, a multispectral monitoring system was installed, utilizing and further exploiting the digital infrastructure developed.

The project of the Holy Aedicule rehabilitation demonstrated that, such a holistic approach is feasible only when the close cooperation between all scientists, technical communities, authorities, and stakeholders is ensured; furthermore, at the same time, this holistic approach eliminates scientific, social, managerial and technical “boundaries”. This cooperation is of utmost importance for rehabilitations of modern buildings and infrastructures as well.

The holistic, digital-driven approach presented herein, departs from the established fragmented-knowledge approach, actively adopting transdisciplinarity, engaging in a multicultural dialogue and achieving inter-scientific reliance. Innovation and Scientific Support are key aspects of such a holistic digital-driven approach and can ensure that this applicable for both historic and modern built environment.

The next step is the development of an adaptable decision support system with the ability to address a wide range of environmental factors, incorporating and utilizing, in an effective and performing manner, all available interdisciplinary knowledge. Such a decision support system integrates diagnosis, prediction, planning, implementation, monitoring and documentation of an asset, within a dynamic iterating process, and can function as an intelligent toolkit for engineers, stakeholders and other relevant authorities.

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