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Digital Twin solutions to historical building stock maintenance cycles

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Abstract. The purpose of this work is to provide a framework for the vulnerability of traditional historical buildings. Buildings that are not constrained and do not have a design obligation for minor energy retrofit interventions. The digitization of the construction sector can help to design interventions with Digital Twin methodologies that can be integrated into a single document that collects them as the Digital Building Logbook. We propose a definition of an innovative workflow that defines integrations and technological innovations in the historical building stock. In this work are presented operational proposals to ensure and increase the protection and conservation of the Italian historical building stock, trying to strengthen the activities of designers and companies for the reduction of seismic vulnerability in case of maintenance or energy retrofit.

1. Context

This paper aims to start an analysis of the opportunities that the digitalization and computer processing of the construction sector can offer for the protection [1] enhancement [2], and security of the historical building stock [3] in light of the innovative technologies and energy transition [4]. A [5] theme that has many implications in the cases of maintenance and management and energy retrofitting. The historicity within the Italian building stock, and specifically that of Rome, is presented from two points of view: that of protection and safeguard as per current Italian legislation [6] and that of the practice of the building process as a technical project is realized by all the actors of the construction sector [7]. This document will focus mainly on the second analysis, evaluating some critical aspects of the traditional historical building stock, protected only in the component of the external building envelope, neglecting the load-bearing masonry structures [8].
According to Mazzarella and Webb [9,10], historical buildings can be classified in two ways: historical buildings (HB) and traditional buildings (TB). They possess three attributes: age, integrity, and meaning built for at least 50 years and that almost always fall among those "listed". The TB traditional buildings are distinguished based on only one attribute: their envelope construction [11]. This latter classification is too vague, difficult to interpret and has significant implications for "traditional" construction [12].

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Most of the Italian heritage building stock does not present stringent protection restrictions as required by current regulations [13]. They can be classified as Traditional Historical Buildings (THB) that are not directly included in the Maintenance and Restoration category of the Code of Cultural and Landscape Heritage. The historical importance of the building is herein regarded in the function of the specific Italian post-unification period (1871–1942). Urban design [14], building types [15], construction techniques and the technology [16] of the material used are not included in any category of particular interest or value to guarantee its safeguarding as foreseen by Cultural Heritage codes [17,18].

In the present work, we want to present the main problems that energy retrofit interventions can have on the building stock [19] and the vast sector of "Traditional" buildings, especially on the structural part of load-bearing masonry. The maintenance of buildings, given the European Directives [8-10] and national laws [3,11,12] on energy performance building [20], requires adaptation [21] and recurrent maintenance of the building-plant system [22–24] .

Seismic vulnerability is the propensity of a structure to suffer damage of a certain level, in the face of a seismic event of a given intensity [13,14]. Italy is a country with high seismicity and valuable historical-architectural heritage, but it is fragile. Any maintenance work must therefore always be carried out considering all the interactions [25] that the supporting structures can have with energy retrofits and transformations of Technical Building Systems (TBS) [15].

It also wants to highlight that the digitization of the construction sector is an innovative process that can increase the level of knowledge of the historical building stock by using computerized tools structured for maintenance and conservation purposes. This ensures completeness and accessibility of data and information otherwise dispersed and not accessible to the construction value chain.

1.1. Historical and urban context

As of 2020, two-thirds of the 35 million Italian homes were built more than 50 years ago and only 9% in the 21st century. From ISTAT data and other sector research [16,17] 73,000 buildings (over half a million apartments) have been recorded and are in a very low state of preservation.

The context of the municipality of Rome is significant for the peculiarity of the building stock and representative of the national and many historic Italian cities [26]. The greatest urban expansion in Rome has been since 1851 when the city was proclaimed the new capital of the nation. It was a period of tumultuous urban development, also known as the "building fever" of Rome [18] during which building production was often found to be at a low level in terms of professionalism and materials used.

Figure 1 shows the plan of the Master Plan of 1883 and the newly planned areas are highlighted in the red squares.

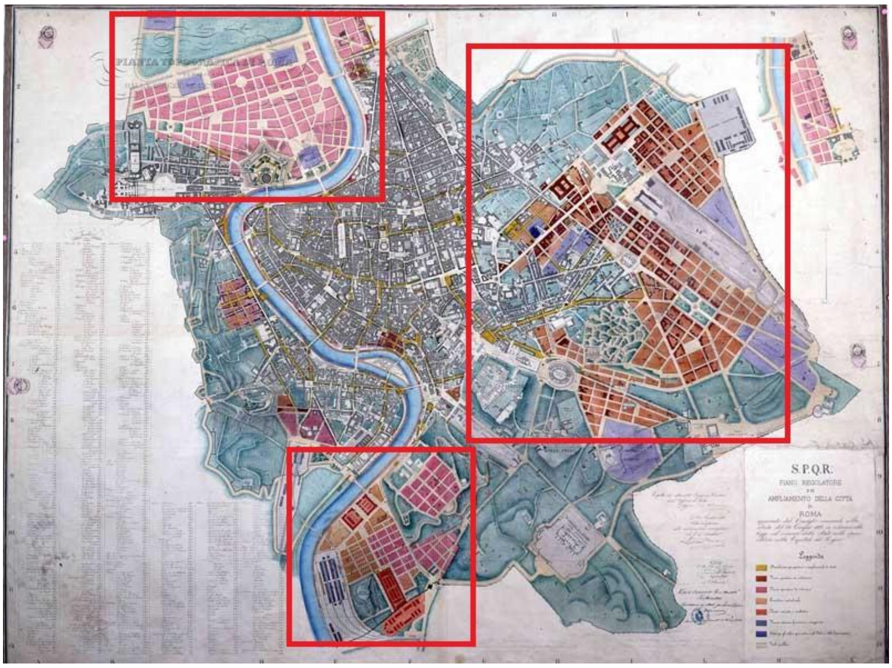

Figure 1: *Rome city plan of 1883 highlighting building expansion areas*

A building that responded more to the needs of quantity than quality. The recurring construction technique was of the mixed type, with supporting structures in bricks and mixed iron-brick floors as shown in the following images.

Figure 2: Walls typical of Rome between the mid-nineteenth and mid-twentieth centuries.

Techniques and traditional construction solutions are typical of the building knowledge of the Roman area, which was used for the entire building period for management and residential use.
Only in 1908, for the fiftieth anniversary of the capital, was designed in Rome the Ponte Risorgimento, the first work made with supporting structures in reinforced concrete [27].
In the municipality of Rome, there are currently 127,713 residential buildings, of which 53,313 have load-bearing masonry structures, 50,806 in reinforced concrete and 23,594 other types, representing 41%, 40% and 18% of the total [28]. If we consider the period of construction, we can see that 31% of

the buildings in Rome are over 65 years old, having been built before 1945. The number of buildings in poor and poor condition is 17,384, or 12.6 % of the total.
The buildings of the historic centre of Rome are the result of multiple mutations, aimed at giving the single building or the single house, in that urban situation, maximum functionality concerning the purposes and habits of housing. These mutations have not always been the result of organic projects that have considered the building organism in its entirety. On the contrary, most of the time they were the result of individual initiatives, which were frequently blind to the risky modification of structural elements, particularly those in load-bearing masonry. Only extraordinary maintenance, restoration, and consolidation are required for interventions on masonry structural systems in the current Master Plan [29]. However, interventions must be designed under current seismic legislation [30]. It is forbidden to modify and alter the structural and wall continuity of entire walls or floors. This leads to barriers to renewable energy even where abundant [31] and possible to be forecasted [32].
Ordinary maintenance work on the THB can be carried out without the obligation of design and communication by the property, designers, and construction companies to the municipal technical offices. But the alterations and impacts on the load-bearing masonry structures, even for small modifications of the TBS, can be high, as can be seen in Figure 3.

Figure 3: TBS placement on historic buildings with a high impact on load-bearing masonry structures

In the present work, we want to analyze in detail a particular type of bearing masonry building built between 1851 and 1945 with building techniques and practices typical of the Roman context of the time: the THB [33,34]. The analysis and evaluation of the effects of energy retrofitting in historical buildings, particularly THB, cannot be left solely to historians and restoration specialists. The use of innovative solutions for computerized management of maintenance cycles is a great opportunity for the redevelopment and safety of all the historical architectural heritage, including the THBs

1.2. Maintenance and conservation of the Traditional Historical Building
The age-old building stock, the absence of seismic criteria in the design as not required at the time, and architectural modification without the appropriate structural checks, are some of the factors that make the Italian building stock at greater seismic risk.
The Italian situation, rich in a building heritage of remarkable historical-architectural and artistic-environmental value, presupposes specific attention to the problem of the overall safety of the building system.
As a result of the energy efficiency policies of buildings, global retrofitting interventions have a high frequency concerning the useful life of the building. Ordinary and extraordinary maintenance interventions on THBs having no legal protection, if not properly designed, can induce structural damage, even irreversible. This situation, in a country with high seismicity and a building stock made

with materials and construction techniques not always to the rule of art must be the subject of careful analysis and subsequent solutions.
Knowledge of the development of historical and traditional masonry buildings is not only essential to the design of new buildings but is essential for maintenance, consolidation, improvement, or adjustment of the existing building stock.

1.3. The Italian Code Framework and the Traditional Historical Building
The Single text of building laws and regulations [35] provides for eight categories of interventions: MO ordinary maintenance, MS extraordinary maintenance, RRC Restoration and Restoration, RE Renovation, New Construction NC, Urban Renovation RU, IC Conservation Interventions, Major IRI Restructuring Interventions. For the MO alone, no documentation will be submitted to the municipal technical offices. In 2016, a Free Building Glossary [36] was issued, identifying the main works that can be performed without any qualifying title, in compliance with the requirements of municipal urban planning instruments and all the regulations of the sector having an impact on the regulation of construction activity (in particular, the anti-seismic, safety, fire safety, health and hygiene standards, those relating to energy efficiency, protection against hydrogeological risk, and the provisions contained in the code of cultural heritage and landscape referred to in Legislative Decree no. 42/2004). In the glossary, 54 main works can be realized without any authorization. Table 1 shows the 15 works that concern the only TBS present in the buildings that can be realized without any communication:

Table 1. Works that can be carried out without any project authorization or approval

N.	Works
1	Vertical lifting systems
2	Sewerage and underground services
3	Electrical system
4	Gas distribution systems
5	Plumbing
6	Fire-fighting systems
7	HVACC system
8	Smoke extraction
9	Heat pump Air-Air
10	LPG thank
11	Freight elevator
12	Stairlift
13	Sanitary appliance
14	Sensory devices
15	Photovoltaic and Micro wind

All 15 works have a safe impact on the load-bearing masonry structures due to the need to create traces, niches and crossings of the walls and floors that go heavily alter the sections with consequent alteration and weakening of the bearing capacities. Maintenance works over the years create a negative and cumulative effect of overlapping effects on masonry structures, also triggering non-reversible effects on the load-bearing capacities of structures [33]. Small ordinary maintenance works in private buildings, which often have significant impacts on the load-bearing masonry structures of buildings, are neither designed nor coordinated by properly trained technicians and designers. The works of

Table 1 are often entrusted to the deontology and professionalism of technicians and companies involved without any regulation concerning the impacts over the years on masonry structures.

1.4. The Digital Twin, Maintenance Cycles, and Retrofit

In the building sector, the complex theme of intervention in existing buildings has different meanings, which oscillate between conservation and transformation. It concerns both the issue of recovery, maintenance, and redevelopment, guaranteeing or improving the original services, and the desire to modify and transform them to adapt buildings to new economic, cultural, and social contexts. The most important inputs for the intervention on the built are the correction of original deficiencies in the construction system: the loss of the original performance levels due to ageing or external agents, the functional adjustment-The European Commission’s Green Paper on energy efficiency in the European Union and the Commission’s Green Paper on energy efficiency. Recently, terms such as "retrofit" or "retrofitting" have appeared in the vocabulary of construction engineering. The concept of retrofit, rather than the restoration or improvement of the original performance, refers to the introduction of new performance, previously not provided or otherwise not provided.

The objective of retrofit interventions is therefore to make effective the architectural and technical characteristics and the performance offered by buildings that are substantially inadequate, with original deficits, in a period of mass construction little controlled or little aware of the multiple requirements to be met. And yet to enhance performance with technologies do not present at the time of construction and, therefore, innovative, represents the scope of retrofit intending to adapt and update buildings. The retrofit is thus placed on a different level than building maintenance because it aims to define new qualities and new performance, originally not provided, to adapt buildings to advanced standards.

The use of innovative technologies and products is a characteristic aspect of retrofit strategies and discrimination that identifies technological retrofit as a particular declination of building requalification.

The most implemented retrofit interventions in the built environment are specifically aimed at:

- -reducing energy consumption through the use of technologies to increase the efficiency and energy saving of buildings;
- -reducing emissions of pollutants and greenhouse gases and their impact on the environment;
- -improve indoor comfort [37];
- -rational use of energy resources through the use of renewable sources to replace fossil fuels [24];
- -promoting new and renewable energy strategies and technologies, optimizing energy demand management [38].

Intervention in an existing building requires reasoning about the inadequacy of traditional design methods and tools [39]. The comparison with the complexity and multidisciplinary nature of the existing project inevitably involves the experimentation of new processes and new technologies able to prefigure and verify the effectiveness of the transformations.

The tool able to offer a control opportunity for retrofit projects is the Digital Twin approach with Building Information Modelling (BIM) tools with 3D models defined as intelligent, able to establish relationships with the other components of the project, from the characteristics of the site, energy performance, the quality of lighting, the number of materials used and their properties, estimation of costs, etc. It is proposed to integrate the needs of the historical building stock's energy retrofit with the innovations offered by the Digital Twin information workflow, to create a digital document that contains all of the information, exploitable databases [40,41] and transformations that occurred over time on the individual building, as will be better described in the following paragraphs.

2. Vulnerabilities of the historical building stock: innovative approaches and solutions

In this paper, we highlight a new concept of vulnerability for THB that considers the possible transformations of the load-bearing masonry structures for each category of intervention provided by the Consolidated Law on Construction.

The technical designer must be able to build, with his knowledge and experience, his level of confidence, able to evaluate the type and mode of energy retrofitting interventions on existing buildings, including THB masonry bearing. The level of confidence must be translated into an analysis methodology that goes from the design phase to the implementation phase. This methodology shall include an assessment by the designer or works director of the absence of impact of the 15 works in Table 1 on the structures.

The vulnerability of masonry buildings in the Roman area has been the subject of studies considering the evolution of residential buildings about seismic hazards [27]. Colozza and Dolce [42] in their research work on the vulnerability and risk of damage to buildings consider necessary an ad hoc methodology for assessing the state of the supporting structures that requires a priority historical analysis of the Roman building that can define the structural characteristics linked to the ways of birth development and transformation. Consequently, the safety assessment and the design of the interventions are normally affected by a different, not necessarily greater, degree of uncertainty.

Energy retrofitting operations, especially on THB, must always be carried out with an approach that takes into account structural problems starting from the single housing unit and contextualizing them to the entire building considering the previous maintenance.

Therefore, the professional skills and qualifications of technicians and professionals, especially in the design and execution of works that impact the load-bearing structures, play a decisive role.

Innovations and training of professionals and the business world play an important role in the protection of the architectural heritage and the entire economic chain.

Also, the entrepreneurial component of the constructions will have to be invested and trained to know and to know how to overcome the criticalities that the energetic retrofitting interventions can have on the THB with some works.

In the entire Italian construction sector, in 2017, 74% of the added value was guaranteed by building maintenance works (123.7 billion); 25% by new buildings (41.7 billion); and only 1% by the installation of renewable energy sources (1.8 billion) [43].

Improvement, adaptation, restoration, and redevelopment are actions that the legislation regulates for a long time and that the approach to the BIM technologies of the built environment could make more streamlined, systematic, and controllable, especially in the light of gradual maintenance that is also hoped for in Circular No. 15 of the General Secretariat of the MIBACT on the theme of "Provisions on the protection of the architectural heritage and mitigation of seismic risk". The intention is expressed in this document to emphasize structural safety through maintenance practices, that is, careful and continuous actions aimed at preventing and eliminating structural fragility in existing buildings through ordinary interventions.

It is, therefore, necessary to have an overview of the above issues, taking into account the interdisciplinarity necessary to find specific solutions for the historical building stock, ensuring the involvement of all stakeholders.

3. Digital construction diary for historical buildings

The digitization of the building heritage through intelligent dynamic models facilitates the access and sharing of information between the different parties involved in the process. Thanks to the interoperability of BIM software that allows the exchange of data related to the building with specific software (structural, energy, management).

The European Commission has developed a framework for the creation of a digital file of the building called "Development of a European Union Framework for Digital Building Logbooks" DBL [44]. The DBL is a dynamic tool that allows a variety of data, information, and documents to be recorded, accessed, enriched and organized into specific categories as defined: "A digital construction diary is a

common repository for all relevant construction data." It facilitates transparency, trust, informed decision-making and information sharing within the construction industry, between owners and occupants of buildings, financial institutions, and public authorities " [45].
The path of digitization of the entire workflow of the building process allows you to create a digital model of the Built-in Digital Twin, to manage in structured informatics mode the entire lifecycle of a building (see figure 4).

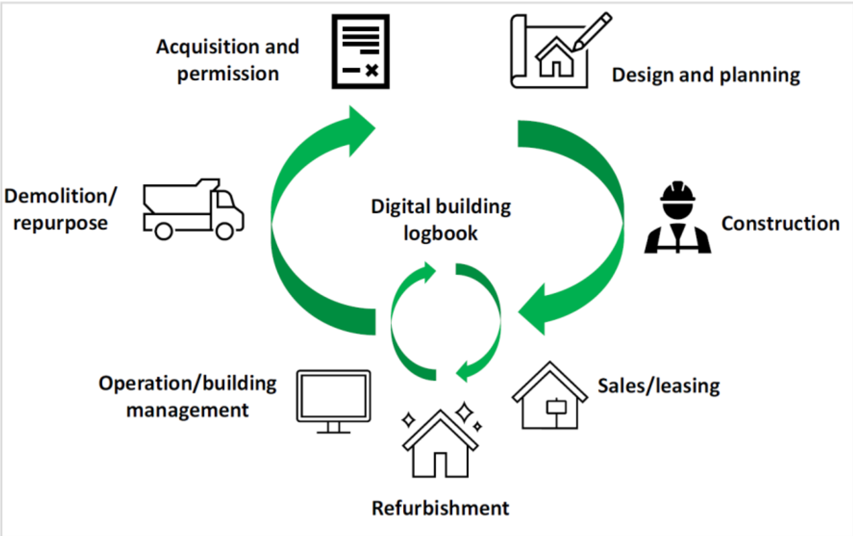

Figure 4 Lifecycle and Digital Building Logbook (Source: Report 1 of the Study on the Development of a European Union Framework for Buildings' Digital Logbook [45])

The DBL allows the maintenance of knowledge over time of the transformations of the building-plant system. Within this innovative document, it is also possible to include the choices and solutions of the entire workflow of the building process concerning THB and all energy retrofitting activities.

- Specifically for THB, the methodology shall contain the following information;
- Historical urban planning framework of the intervention;
- Research and analysis of project documentation as well as all previous interventions and works;
- On-site surveys, photographic, geometric, and non-destructive surveys in a Digital Twin modelling perspective;
- Recognize the architectural and mechanical language of masonry construction;
- Provide a fast building quality index (IQM) of the housing unit contextualized to the entire building
- Avoid mechanical, physical, and chemical incompatibilities;
- Aim for a minimum of intervention, including safety and conservation;
- Evaluate the interaction of the building under consideration within the building aggregate, if any.
- Planning of destructive investigations commensurate with project interventions
- Impact assessment and possible design solutions (mitigations) of interventions on load-bearing masonry structures
- Production of complete reports certifying the solutions adopted to be integrated into the digital booklet of the building in Digital Twin optics and the function of the DBL.

The Digital Twin strategy and the creation of a design workflow with HBIM Heritage Building Information Modelling tools can be integrated into the DBL. This integration of innovative procedures and tools represents a great opportunity for the protection and safety of all the historical Italian building stock.

4. A comprehensive proposal on the historic building stock

This paper is a first step to defining an innovative approach using Digital Twin modelling solutions aimed at DBL for a reorganization of the entire building process maintenance of THB involving all actors: technicians, public administrators, and construction companies.

The analysis was carried out on the three macro-areas: Traditional Historical Buildings THB, Seismic Vulnerability, and Energy Retrofitting Cycles ERC through a cross-cutting approach that allowed us to define an innovative workflow specific to the category of THB. The result is an integration of knowledge and procedures between Digital Twin and DBL that allows the definition of a strategic document for the maintenance, protection, and security of the historical building stock, and in particular of the THB that needs specific approaches and solutions.

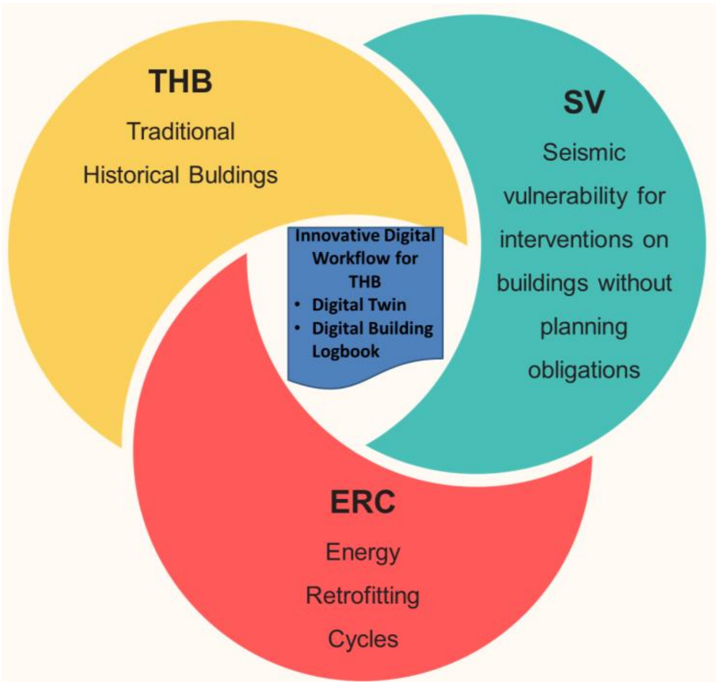

Figure 5: Proposed innovative workflow for the maintenance cycles and retrofit intervention on the THB

Much work must also be done to raise awareness and theoretical and practical knowledge among all actors involved in interventions on historical building stock, particularly THB with energy retrofitting works that affect load-bearing masonry structures.

It is a necessary path to improve the formation of the technical and economic parts of the construction sector for the protection and conservation of the entire Italian building stock. Not only the regulated and listed, but also the THB, are exempt from the constitutional principle of protecting and preserving historical and artistic heritage.

5. Conclusions

Buildings have a life, and their life depends on how they were conceived, but above all, on how they are managed and maintained. Over time, technology has put us in a position to improve materials and, with the digitization of the construction industry, the entire workflow of the building process.

Digital transformation is at the basis of the change in the real estate and construction sector, especially with the introduction of the Digital Twin, the digital twin of the building, which allows the virtual visualization of all assets, processes, data, and key elements for the management and maintenance of the property.

Historic buildings have unique characteristics that must be addressed in an innovative workflow that only the Digital Twin approach can guarantee. A structured collection of information and data on the maintenance and management of such an important but fragile architectural heritage helps to achieve economies and efficiencies in many respects. In the case of THB, what is presented in this paper is intended to be a support decision to have analysis and control procedures that do not currently exist for the protection of load-bearing structures.

The DBL is therefore an indispensable tool for monitoring the conservation status of the historic building stock. To identify and codify THB risk situations and plan long-term maintenance, restructuring, and structural consolidation to improve the quality of the same, as well as to adapt to maximum energy efficiency levels and reduce seismic vulnerability.

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