Application of dynamic and AI approaches for predictive maintenance

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***Abstract*— The paper deals with the application of AI for predictive maintenance. It is the result of multidisciplinary ongoing research conducted by the Department of Architecture (DiARC) of the University of Naples Federico II, Department of Civil Engineering and Architecture (DiCAR) of the University of Catania, and ETT S.P.A., a leading company in Digital Transformation. The objective of the research is to demonstrate how new Information and Communication Technologies (ICT) technologies, in the era of Smart cities, can be used not only for managing and monitoring new buildings but also in the context of built heritage to protect it, through an optimized approach for the planned maintenance. ICT can revolutionize maintenance, especially from Facility Management perspective. In this sense, Artificial Intelligence (AI) and Internet of Things (IoT) systems can optimize maintenance processes, enabling knowledge automation. It is possible to delineate statistical models related to built heritage performance over time by analyzing, interpreting, and systemizing Big Data from heterogeneous sources, moving from reactive to proactive approaches. The method involves a first phase characterized by a condition-based maintenance strategy and then moves to a predictive maintenance strategy. By learning from itself through the use of AI, the proposed system predicts degradations and failures even before they occur: the asset preservation guarantee is increased, and consequently, so is the useful life. Testing AI on a case study will also demonstrate how much the application of automation systems in predictive maintenance processes can lead to savings in economics, time, material, and labor compared to traditional scheduled maintenance systems.**

Keywords—predictive maintenance, IoT, AI, Machine Learning, Smart Cities, Architectural Heritage

I. INTRODUCTION

Cities are facing significant challenges related to population growth, urbanization, and environmental impact [1]. The smart city seems to be the inevitable model for the development of the contemporary city [2]: the available technologies allow the realization of human-settlement interconnections that ensure, through smart governance, a higher level of livability for citizens and communities while addressing current energy and environmental emergencies [3]. In this context, smart building management is crucial [4]. Smart systems also aim to improve the maintenance of physical assets such as buildings, bridges, and roads. There are numerous examples of smart monitoring systems for the built system [5] [6] that, through IoT devices and sensors can monitor and manage energy consumption, indoor air quality, and other factors, thereby reducing costs and improving the occupant experience [7]. So, in the smart city philosophy, every process, as well as maintenance, is automated through enabling ICT technologies, starting from IoT sensors for real-time data collection to information management and interpretation systems [8].

In this scenario, it is essential to include the conspicuously built heritage that constitutes the settlement system in smart city actions. The maintenance of the existing is as important as it is underestimated: the idea of maintenance as a process needs to be promoted, favoring prevention and care strategies rather than more invasive interventions [5]. Over time, the concept of maintenance as repairing a failure has been progressively superseded by maintenance culture, which "refers to the ability to predict deterioration and to plan interventions, with a strong economic implication related to the property value of the object" [9].

The activities of observation, planning, and control, typical of the maintenance process, can collect and systematize large amounts of data, implementing information systems, essential for decision-making support [10]. In this sense, new technologies applied to existing assets should work not only to assist management but also for data interpretation. Determining a certain degree of prediction about failures and degradations makes it possible to do smart maintenance.

The research conducted by DiARC, DiCAR, and ETT s.p.a. is ongoing and in the experimental phase. The research aims to demonstrate how new ICT technologies, in the era of Smart cities [11], can be used not only for managing and monitoring new buildings but also in the context of cultural heritage to preserve it, through an optimized planned maintenance approach. The methodology for planning maintenance activities was organized in two times: an analysis time and an operational time.

The use of traditional but innovative tools applied to “time zero” which is the time of analysis and knowledge, was made through the application of Patent No. PD2009A000153 "A system for the planning and control of maintenance interventions in a spatial element of a building system" (2012), the result of research of the University of Catania (Prof. Stefania De Medici, PhD Carla Senia).

For the operational time, meaning in the monitoring phase, we made use of an innovative tool designed for conducting visual inspections. MUST (Maintenance Urban Sharing Tool) is an application developed in partnership between ETT s.p.a., DiARC, and DiCAR of the University of Naples Federico II and Stress Scarl, which makes use not only of IoT and AI devices but also of users to report faults and degradations, incorporating the interconnection logic proper to the Smart City.

The case study is the Strega-Alberti factory, located in Benevento, southern Italy. The building complex was selected both because it is characterized by strong material and immaterial values and because of its complexity, especially management complexity, which is essential to controlling interference between production and maintenance activities.

The paper is divided into four main sections. The first one concerns the background and aims to highlight the importance of maintenance as a strategic tool for protecting existing architectural heritage and the use of new ICT technologies to support maintenance activities.

The second section concerns the case study, which enabled the development of the maintenance plan optimization system. Based on dynamic optimization logic and AI, the methodological approach is divided into zero-time and operating-time.

The third section concerns results and discussion related to future developments of the method and the potential of the maintenance-new technology combination, which will lead to new professionalism and conclusion.

II. NEW TECHNOLOGIES FOR THE MAINTENANCE OF ARCHITECTURAL HERITAGE

Buildings are responsible for approximately 32% of global energy use and 19% of CO2 emissions. Their longevity and ability to reduce these values have made them a significant priority for emissions reduction [12]. The increasingly expensive resources and the development of information technology encourage the growth of smart building management. The IoT is the main driver in the development of smart buildings [13]. In this context, managing buildings most efficiently is critical, and maintenance plays a key role. Furthermore, for the past few years, the construction industry has been facing, with difficulty, the digital transition, commonly known as "Construction 4.0," where data interoperability and automation are the main goals [14]. In this direction, the paradigms of change for the building management and maintenance industry are represented by new and rapidly evolving ICT technologies, such as the IoT, smart sensors, cloud computing, Extended and Augmented Reality [15], BIM, Digital Twin (DT) [16] and AI [17].

Maintenance is a key sustainability strategy because "with maintenance, the value of available urban capital is kept constant over time, and thus sustainability is promoted: maintenance and sustainability are closely related to each other" [18]. Maintenance aims to maintain the performance of a building asset over time, thus counteracting a decrease in value, not only economic but also cultural, social, and environmental, allowing it to be transferred to future generations, aligning with sustainability principles.

The management phase of a building is essential in the life cycle of real estate assets since, together with maintenance, it represents the phase with the highest impact compared to the global cost [19]. For several decades, the field of maintenance has been linked to Facility Management (FM) [20]. However, the desired benefits have not been achieved in Europe, neither in terms of asset preservation and enhancement [21] nor in terms of optimization of management and maintenance processes [22].

Several studies have shown a positive change trend in the maintenance management research field. One theme discussed is related to the decision-making process, which includes both the lack of policies to incentivize maintenance and the issue of citizen involvement in urban care practices to address the problem of reduced economic resources for maintenance [23]. Another topic that is mainly discussed is the integration of new digital technologies, both for new construction and for the existing built heritage, intending to acquire information for the definition of databases necessary to optimize maintenance processes and to build digital models, useful for simulating the mechanisms of performance decay of technical elements over time [24]. A third research topic is the assessment of decay and the most appropriate maintenance techniques: a mismatch is identified between theory - maintenance program and design - and practice, which is often too limited due to scarce dedicated resources and lack of information [25].

Information is a fundamental key to the efficacy of the entire maintenance process [26]. Information is a foundational prerequisite for decision-making activities, which is the critical transformation of information into actions: information is the base of maintenance success [27]. Information gathering aimed at implementing information systems is a heritage of industrial origin related to the observation and learning phases of systems in service [28]. A maintenance information system is defined as "a complex of standards, procedures, and tools designed to collect and process the information necessary for the management of maintenance activities and the monitoring of facility activity," - although for the building system, it is necessary to speak of a management system. The UNI 10951:2001 standard defines the Building asset Maintenance Management Information System as a "decision-making and operational support tool consisting of databases, procedures, and functions aimed at collecting, storing, processing, using and updating the information necessary for the setting, implementation, and management of the maintenance service" [29].

Therefore, to increase the management quality of the built heritage, it is necessary for maintenance to be based on dynamic, data-centric real-time approaches that promote the standardization of procedures and communication flows, supporting maintenance-related analysis, planning, and control activities [30]. An information system that collects Big Data must be structured according to the characteristics of the building - i.e., its level of complexity or its intended use - and the needs of the owning entity concerning the principles of manageability, data availability, integrability, consistency, and security. The data collected are strategic because they can assume a triple function, alternative or complementary, of prediction, comparison, and knowledge/feedback [27].

New ICT technologies can support the detection and management of large amounts of information, influencing environmental redevelopment processes. This approach results in a multi-output maintenance strategy that varies depending on the object, the client, and the quality levels required [30].

In particular, through the use of AI, it is possible to analyze, interpret, and systematize data collected through IoT (dynamic real-time information) with databases (static information), outlining statistical models related to the functioning of the building and its technical elements [31]: thus moving from reactive to proactive approaches [32]. In recent decades, Machine Learning and Deep Learning have revolutionized many fields such as medical diagnostics, robotics, economics, social sciences, and others [33]. In construction, AI is currently undergoing experimentation for different building life cycle stages [34]. In maintenance, AI is applied to reduce the risks, time, and costs associated with traditional building inspections [35]. It is possible, through the use of machine learning and deep learning algorithms, to automatically recognize faults from photos [36] and generate predictions (of faults, for example) based on past experiences [37].

III. METHODS AND MATERIALS

The research is ongoing, and the case study selected is the Strega-Alberti factory, located in Benevento, southern Italy. In the first instance, the building complex is well suited for experimentation with significant results because it is a production site where downtime due to breakdowns is to be avoided. The main requirement of the factory is never to slow down or stop production, thus placing the need to reduce interference between production and maintenance activities at the forefront. Secondly, it is a building whose cultural value is characterized by both material and immaterial values. The factory is the emblem of the local production culture of liquor and confectionery products. Still, it is also the scene of cultural production in design and art. In addition to the intangible values, there are also material values. The current building results from transformation and modifications resulting from production needs that go along with the evolution of production technologies. The building is a veritable handbook of architectural technology that testifies to construction technologies that change over time.

To start from a base for experimenting with the method, which can potentially be expanded to the entire factory, the liquor bottling area was taken as a reference.

After an initial knowledge phase, the functional characteristics of the building, such as the frequency of activities, were investigated to define and calendar production and stop days. Fundamental to the research was also the analysis of the users, divided into primary (carrying out the main production activities), secondary (carrying out production support activities, such as cleaners, etc.), and occasional (represented by occasional visitors). For each type of user, dwell time and frequency within the space element were evaluated.

A methodology for planning maintenance activities was then defined within the experimental field based on dynamic optimization logic and AI.

The methodology is divided into two times (Fig. 1).

At "time zero"- the time of analysis and knowledge applied to a pre-operational phase - as specified above, a traditional but innovative method is applied. The starting point was the application of patent No. PD2009A000153 "A system for the planning and control of maintenance interventions in a spatial element of a building system" (2012), the result of research of the University of Catania (Prof. Stefania De Medici, PhD Carla Senia). At this stage, the first drafting of the timeline occurs, optimized according to user-defined intervention priorities. In an FM logic, the tested system can cross the users' needs with the efficiency required for the building system allowing the optimization of the maintenance activities according to a method structured on three optimization levels: the first one provides a hierarchy of the required efficiency conditions, the second one evaluates the maintenance sets, and the last one allows the verification and management of interferences. The logic of Task Analysis, the analysis of user types behaviors in the actual context of use, is applied to schematize users' activities and understand their needs, study their flows, and manage possible interferences with inspection and maintenance activities. Starting from user actions, it is possible to define usage requirements that must be guaranteed within the space element. The system provides for the active collaboration of users in evaluating inspection and maintenance priorities for action. In this case, a multi-criteria decision-making tool was used to facilitate users in defining intervention priorities through pairwise comparison. The result is thus the possibility of defining a scale of intervention priorities on the technical elements that make up the building system: for example, in the bottling area, it is a priority that the French doors, which allow the flow of goods, be maintained. This first phase carried out at time zero, enables the definition of a maintenance plan that is optimized to meet the needs of the activities settled in the building.

In brief, the developed method, in its first phase, allows for optimizing the schedule of maintenance activities according to the activities carried out in the buildings, according to priorities indicated by the users themselves, and thus concerning the needs of the activities settled in the building [38]. The patented system transfers analysis methodologies (Task Analysis) and evaluation tools (Quality Function Deployment) from other disciplinary fields (management engineering, industrial design, ergonomics) to the field of maintenance activity management [39].

The maintenance process and schedule are further optimized during a second time, the "operating time," through the use of the MUST application, an innovative participatory maintenance and management system that makes use of various tools for monitoring the built environment and that, thanks to the latest technological developments and the application of AI, can learn from itself and thus progressively improve the predictive capacity for failure and degradation.

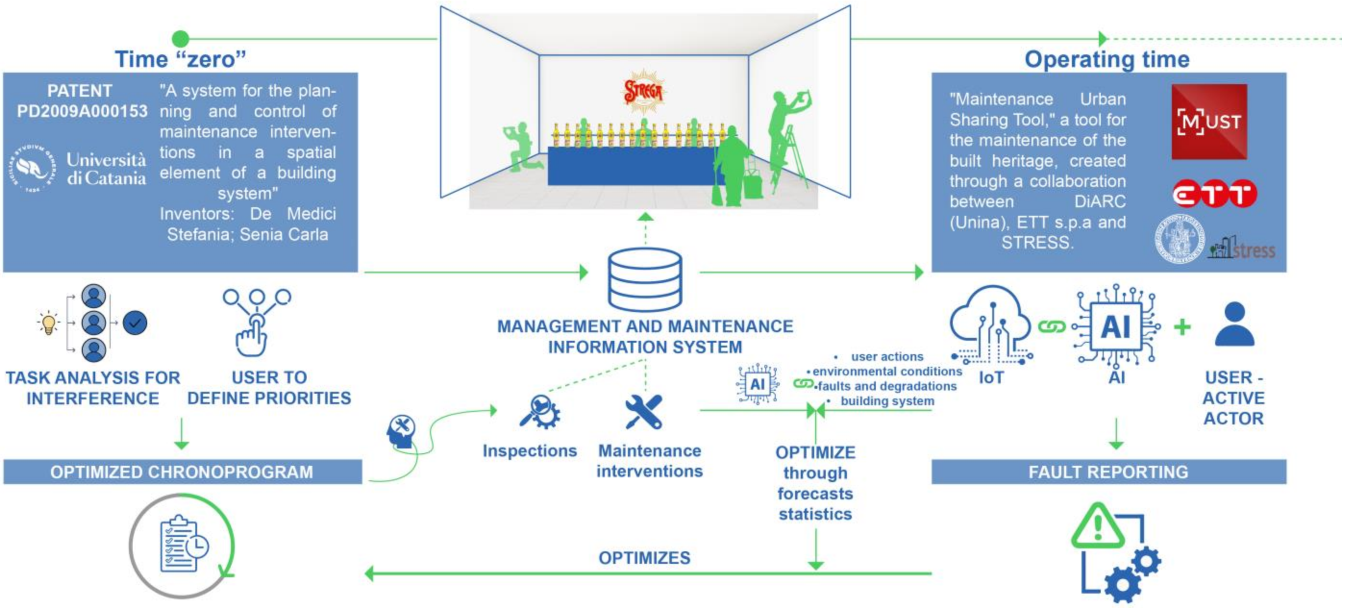

Fig. 1. Methodology outline

MUST was born as a failure reporting tool made available to non-expert users: through an application installed on mobile devices, in fact, users of the built environment report failure in real time. MUST's application is equipped with AI to support the reporting phase for recognizing and classifying degradation or failure and to reduce the risk of entering incorrect reports or duplicates of existing reports into the information system. The application, thanks to the collaboration with the Department of Computer Science, Bioengineering, Robotics, and Systems Engineering (DIBRIS) of the University of Genoa, is being tested and sees the support of a neural network, powered by machine learning, for the classification of the types of faults photographed.

MUST collects and cross-references information from user reporting within its information system, bringing it into a system with Big Data from two other primary sources: cameras and IoT sensors. The cameras enable constant monitoring of the spatial element and the performance of user activities. Through the application of AI, camera videos are interpreted; thus, user behaviors can be statistically detected, rather than abnormal events that may lead to the occurrence of failures or accelerate degradation processes. On the other hand, through the installation of IoT sensors, which constantly monitor the indoor environment in terms of, for example, relative humidity, temperature, and IAQ, it is possible through AI and the adoption of algorithms to notice any abnormal changes, sending alert notifications to the central system. All information related to the building system, detected through MUST, goes to implement the information system that relates user actions, environmental conditions, faults and degradations detected and observed over time, and building system data.

In addition to reporting failures in advance through AI, the system enables further optimization of the schedule by improving the predictive capacity over time. The methodology presented leads to the implementation of a condition-based maintenance strategy that over time, as it refines through the application of AI and then learns from past inspection and maintenance activities, moves toward a predictive maintenance strategy, allowing the detection of failure and degradation even before it is identified through inspections.

IV. DISCUSSION AND RESULTS

The research results from a multidisciplinary system in which different studies and experiments have been brought back into play to achieve adequate maintenance planning in architectural heritage, exploiting the potential of new technologies.

The use of the patent as a starting point for the definition of a methodology applicable at time zero, has allowed the definition of intervention priorities derived from the real needs of users and the factory's production; in addition, the application of an innovative methodology with MUST has allowed the experimentation of integrated and innovative monitoring techniques that, taking into account, the needs already examined in the first phase and then an adequate timetable, enables an update to and real-time analysis of the evolution of degradation phenomena and failures as well as a constant control of the quality of the systems.

In particular, the patent application had already been tested on the heterogeneous real estate assets of the University of Catania, characterized by different types of users and activities. In fact, following an analysis of the real estate management system, the need to increase maintenance services at the university campus emerged. The schedule optimization method was employed in a classroom for teaching in a sample building. By breaking down user activity, usage requirements were defined. Through questionnaires, classroom users were asked to assign a weight to each requirement to express the importance of different technical elements concerning the performance of everyday activities. In this way, through a qualitative rating scale, it was possible to prioritize interventions for the needs of the classroom users.

On the other hand, the MUST application had already been experimented with the project of a Digital Twin of the Porto Antico of Genoa. The "DSH2030" project - Digital and Sustainable Harbour 2030 (https://www.digitalsustainableharbour.it), supported by the POR FESR 2014-2020 funds of the Liguria Region, led to the preparation of a digital twin of the harbor that, through the integration of machine learning and sensor technologies, was able to define a new model of sustainable management and maintenance for the tourist harbor. Within this project MUST played a key role in supporting the monitoring activities of the entire area managed by the Società Porto Antico SpA and especially of the essential buildings that characterize it and that are the result of the redevelopment designed by Architect Renzo Piano. Within this project, the application potential had already emerged: to facilitate the management processes of complex areas and buildings and to provide a constant flow of data for the Digital Twin. The amount of data collected in real-time was helpful in the start-up process for predictive maintenance of the area [40].

The current research experiments with optimizing inspection and maintenance processes by bringing two already extensively validated tools into a system for the first time.

V. CONCLUSION

Using new ICT technologies to support information systems can help overcome the critical issues of planned preventive maintenance, as failures can be intercepted before they occur. The current study, which continuously and dynamically monitors the building system, aims at a predictive maintenance strategy. The human-centered view of the developed system is based on active user involvement in maintenance planning and execution. The combination of two already extensively validated tools defines a maintenance management model that includes an in-depth analysis of the users and their needs and organizing a "maintenance service, which, responding to the instances of expanded sharing of responsibilities with the involvement of multiple competencies, activates synergies between the scientific contribution of expert knowledge, the information potential of users and users, and the operation of the technical component." [41]. In this view, users move from being on the outside of information processes and decision-making to becoming active participants, even if with limited knowledge. MUST is a virtuous example in this sense, applying knowledge-sharing paradigms to maintenance. User collaboration will dramatically reduce on-site inspections, solving most maintenance problems remotely. Moreover, the system will be able to learn over time and develop a specific ability to detect and predict the evolution of the degradation of the observed site, thanks to the massive feeding of photographs and data acquired by the user's application.

This project aims to establish coordinates for a permanent maintenance site by providing a digital platform, enabling a real contextual maintenance community [41]. Users can report failures and degradations they can perceive via mobile devices, starting from a well-defined schedule based on the real needs of production and users. Expert knowledge, supported by AI, coordinates the context of the information. On the one hand, it considers the fault signal sent by the user and the IoT multisensors. On the other hand, it critically systematizes the information gathered with construction technologies, priority control, available budget, and professional management [6].

The approach proposed in this research will only be feasible with the involvement of highly skilled and multidisciplinary teams. Maintenance supported by new ICT technologies and AI will, therefore, lead to developing a new professionalism. It renews the maintenance process, especially in its extreme stages of planning and control, through a method that can identify the needs of the actors and respond to them in an appropriate and timely way.

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