INSPIRE PROJECT : INTEGRATED TECHNOLOGIES FOR SMART BUILDINGS AND PREDICTIVE MAINTENANCE

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Commission IV, WG IV/1

KEY WORDS: Digital documentation, key enabling technologies, BIM, Bigdata, integrated digital platforms

ABSTRACT:

Applying integrated digital technologies for the management and maintenance of the existing built heritage appears to be one of the main current challenges for the definition and application of digitisation protocols for the construction supply chain. Key enabling technologies, collaborative platforms, Big Data management and information integration in a BIM environment are areas of increasing experimentation. In the field of intervention on the built heritage, it is the boundaries and opportunities offered by the integration of many different information sources that constitutes the main challenge. Furthermore, the study of the accessibility and usability of data and information from sources such as the three-dimensional terrestrial survey, existing databases, sensor networks, and satellite technologies make it possible to investigate both different ways of data modelling, even with a view to the development of predictive algorithms, and of visualisation and information management. The study illustrates part of the results of the InSPiRE project, an industrial research project financed with European structural funds and carried out in a public-private partnership by four universities and public research bodies, an innovation centre and six companies, SMEs, large enterprises, and start-ups. Specifically, the project highlights the growing importance of BIM-based modelling as a tool to lead users, both experts and non-experts, through the multiple information paths resulting from the relation between data and metadata.

1. INTRODUCTION

Increasingly, key enabling technologies –sensors, Big Data, cloud computing and systems integration– are being explored in the construction supply chain, which was traditionally characterised by a number of barriers to the introduction of technologies aimed at industrialising the value chain (European Commission, 2021). An increasing acceleration in the direction of effective data interoperability in favour of integrated collaborative projects is being registered. Starting with the processes of introducing Building Information Modeling tools and methods, with particular reference to the supply chain transformation processes started first in the United Kingdom, since 2009, and later in the other EU members, the foundations are being laid for the development of integrated digital environments.

Thus, integrated design is fostered by the implementation of IFC standards on the one hand and the sharing of operational standards on the other, such as the dissemination of ISO 19650 standards.

However, the value chain of project development and, in particular, of intervention in the built environment is still characterised by fragmented information and heterogeneous sources of data that need to be put in relation. Indeed, enabling the synchronic comparison of diachronic scenarios and fostering the ability to organise information and make it available as structured know-how, from the scale of the individual intervention to the scale of the urban compartment or urban regeneration, is a primary objective of the value chain (Zhao, 2022). Implementing and expanding access to technologies for documenting the state of buildings, cities and territories is a key enabling factor (Bianchini et al., 2021).

Integrated technologies of three-dimensional surveying, terrestrial laser scanning, drones, photogrammetry, technologies for continuous or discrete monitoring of energy performance indicators, environmental comfort, structural and seismic safety are just some of the data sources that can be integrated now, even in the early stages of project development.

Consequently, it is necessary to develop effective visualisation and digital representation models that are correlated with the geometric and morphological characteristics of the building or urban fabric to be analysed, on the one hand, and on the other hand, to avoid the reproduction of the same data in a different form, to implement data interoperability protocols.

2. RELATED WORKS

The development of an integrated digital platform for the maintenance management of the existing building stock, also from a predictive perspective, starts from the implementation of technological backgrounds implemented by members of the research partnership. Solutions are implemented on the one hand from systems and technologies for intelligent monitoring of safe infrastructures (Aleixo et al., 2020) and on the other hand from multi-spectrum sensor integrations for specialised monumental buildings. The project is developed by an experienced public-private partnership within the Clust-ER BUILD and the Emilia-Romagna Region's Intelligent Specialisation Strategy. The Clust-ER BUILD is an association of public and private stakeholders, universities, CNR, enterprises, trade associations, public administrations and third-level training centres that define strategic objectives for industrial development and the territorial ecosystem. Permanent working tables define and update priority development areas such as the development of integrated solutions and services that foster the application of key enabling technologies.

At the same time, the implemented solution is designed to promote skills upgrading in the areas of digitisation and Industry 4.0, in order to respond to the strategic thematic areas of the EU Cohesion Policy 21-27 (Arbolino, Boffardi, De

https://doi.org/10.5194/isprs-archives-XLVIII-4-W3-2022-127-2022 | © Author(s) 2022. CC BY 4.0 License.

Simone, 2019), such as open data, smart technologies and social inclusion.

3. DEVELOPED METHODOLOGY

The InSPiRE project implements the design of a predictive diagnostics system for monitoring the status of preservation of existing architectural heritage materials, components, and systems that are reaching the end of their useful life under normal working conditions. Networks of wireless sensors based on smartbrick technology are implemented using various monitoring and data acquisition technologies, and case studies of social public housing have been placed under continuous monitoring for the development of a predictive algorithm (Galdelli et altri, 2022) primarily aimed at evaluating the static and seismic safety of the buildings examined. The Mu.S.A. Multisensor Assessment for Cultural Heritage platform, which was funded under the Por Fesr Impresa 2015 call and integrates the different levels of information on the monitored subject's operating status, ensures the acquisition of information from the sensor network and the management of the dataset originating from the diagnostic campaign by multispectral images, integrated with the monitoring by potentiometers, strain gauges, and inclinometers. The result is a strategic decision-support tool for predictive maintenance and management activities that, by conducting intervention procedures on an existing built heritage, enhances its useful life and capitalizes its economic value under boundary conditions of operation and/or emergency. The involvement of market-leading companies in the production of materials and systems for intervention on the built heritage, in the management and processing of big data, and in the development of advanced sensors supports the implementation of the platform architecture, contributes to the validation and demonstration in the relevant environment (TRL5-6), and to the demonstration of the prototype (TRL7). In order to develop the architecture and functionality of the platform, the following system requirements were also defined and implemented:

- Integration of data and information from existing databases, such as the Acer intervention archive, through the implementation of data exchange protocols;
- Integration of data related to the actual state of the built heritage surveyed, cartography, three-dimensional models, surveys, and diagnostic investigations of materials, components, and systems;
- Integration of data at the spatial scale from different sources such as satellite data for the assessment of subsidence phenomena.

Figure 1. Some case studies of social housing implemented in the InSPiRE project.

3.1 Digital documentation and Big Data

When it comes to the construction industry, data is frequently not available in a structured format that can be easily pigeonholed into rows and columns, but it is available in the form of documents, meta data, geographic locations, values sensed by IoT sensors, and a variety of other formats, ranging from semi-structured to completely unstructured.
The data that make-up Big Data archives can come from heterogeneous sources, such as website browsing data, social media, desktop and mobile applications, mathematical models, and-increasingly-internet-of-things sensors and devices.
A system based on and aimed at data-driven management of the built environment must be able to respond to queries not only related to the state of affairs or recent interventions but to actions historicized over time. The technical skills, both theoretical and practical, for the design and development of Big Data applications require a specific domain in the field of IT, which must, however, as emerges from the present project, be complemented by specific skills specific to the application domain; the construction sector in this case.
The solution implemented as part of the InSPiRE project employs specific tools for Big Data processing such as: Hadoop, Spark, NoSQL, in-memory databases and analytical software. Other skills, however, are related to disciplines such as data science, statistics, data mining, quantitative analysis, data visualization, programming in general and for specific languages machine data structuring and algorithms. Lambda Architecture is the reference architecture for the development of the platform that exploits the concept of building a system for managing Big Data in a series of layers; each layer meets certain requirements and exploits the features of the layer below. At the lowest layer, the lambda architecture is responsible for saving raw data and "precomputing" views from it. Each view is the result of processing raw data and not successive layers of computation in order to avoid operator errors in transferring or processing the data. Hadoop is the reference technology for this layer.
The Batch Layer typically characterized by a distributed NoSQL database has the task of saving the data of the underlying layers and by construction must be efficient mainly in "block" updates of information and random reads (non-sequential, hence queries), a feature that allows not to add complexity in the systems. Finally, the Speed Layer is entrusted with handling the latest data and updates the real-time view individually whenever it receives information.
The speed layer, therefore, performs an incremental computation and not a recomputation as in the batch layer.
The speed layer has limited time validity, just long enough for a recomputation of the batch layer to occur: Complexity Isolation. That feature has proved to be of particular relevance for applications in the context of the value chain of the existing built environment in which not only the visualization of information in a variety of modalities-graphs, maps, diagrams-is of central importance for the effective definition of intervention and project scenarios, but at the same time the capability to update information by considering constantly changing "blocks" and information categories without changing the architecture of the system, except as a result of training of the computational algorithms is essential.

3.2 Frontend, backend and data visualization

Integrating the diagnostics module and the predictive module led to the implementation of the new InSPiRE Monitoring Platform through implementation of the Mu.S.A. technology background. The "Monitoring & Control Portal" provides a comprehensive tool for managing the monitoring and diagnostics process, allowing to manage the steps necessary to implement data collection and analysis on the built heritage.

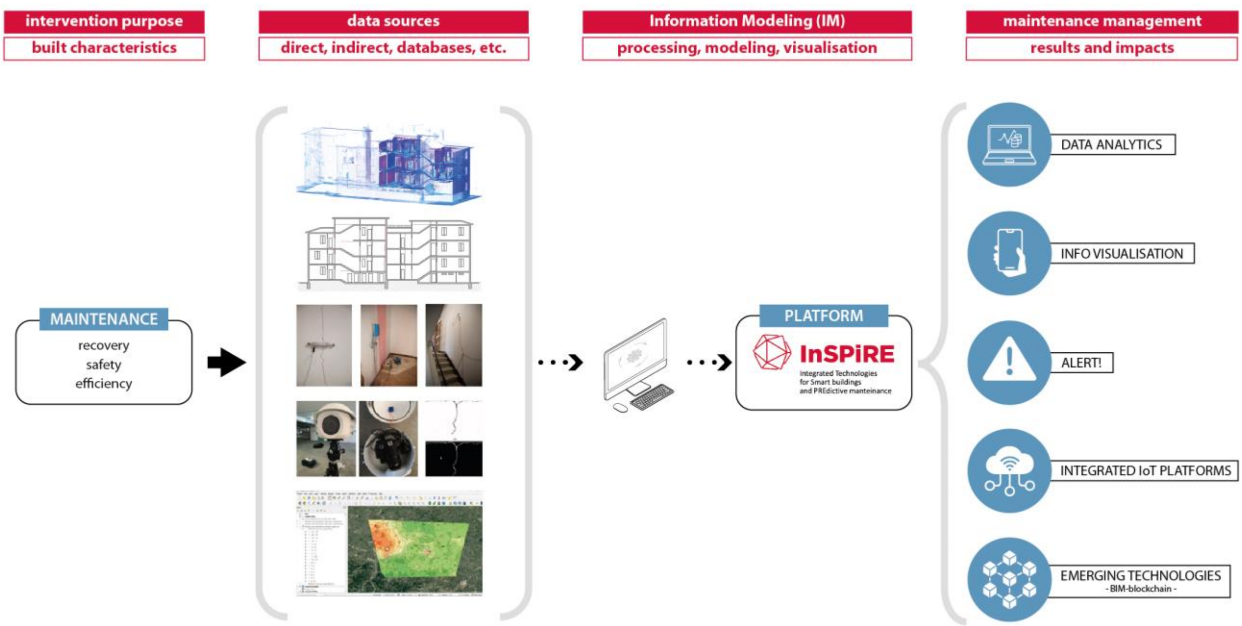

Figure 2. Data integration from various sources for predictive maintenance of the built heritage.

The realized platform can support incoming traffic from any network (IoT and non- IoT), capable of collecting, saving and analysing the collected data. The integrated solution thus developed has been distinguished into areas with different functionality. The main functionality is the Dashboard Home: the portal displays using maps and/or Dashboards the data recorded by the acquisition system, with summary indexes of the status of the monitoring (Census Buildings, Active Monitoring, Alerts, New Buildings, etc.). It also consists of three separate thematic tabs for: map, Alerts, Buildings. The Map tab presents the actual status of the monitored area with feedback regarding different sources of information arranged on different levels that can be activated as desired: "Buildings with monitoring status," represented with icons of different colour and shape according to the monitoring status, can be queried via pop-up menu containing an overview of the building from different points of view (e.g, informational, energetic) from which the full building tab can be reached; "Radar points" on the map with relative colour code established according to the 'vel up' parameter; "Subsidence map" whose activation highlights the speed of ground movements with relative areas by colour code; "Isometric curves" distinguished by colour code; "Energy consumption" allows viewing the classification of the analysed area areas by energy consumption class, associating each class with a certain colour on the map. The Alert tab, the dashboard tab set to show any anomalies found on active monitoring, provides three different types of alerts: "Interruption of communication" alerts the user when a particular device will stop sending data; "Values detected out of scale" when the data recorded are unrealistic as they are higher (orders of magnitude) than normal values, implying an anomaly in the sensor or incorrect conditions of use; "Deviation on alert values" identifies the exceeding of threshold parameters that underlie critical conditions during the acquisition campaign. The Buildings tab is the tab from which, through a filterable and searchable table, it is possible to access the 'list of monitored buildings, complete with acquisition status and related links to available data (i.e., 2D and BIM processing). The second feature is the Basic Archives, which stores the basic elements of the portal divided into "Building Master" reports the area dedicated to: Data, Documents, 3D BIM Models, etc. Feeding the system when fully operational can be done directly from the portal or through Import and/or access to existing applications in which one building can be matched to one or more categories through which to form logical aggregates of buildings. Each registry will consist of: Building Tab (i.e., Identifier and Master Data, Monitoring, Survey State, Diagnostics, Typological and Construction Characteristics, Structural Characteristics, Energy Characteristics); 2D Visualization; BIM Model for navigating the digital twin and accessing the source of the recorded data; Monitoring identifies each object capable of directly communicating/providing data to the Acquisition System and allows direct access by querying images, specialized documentation, and the dashboard with widget showing the data acquired from the device.

An additional feature is the Materials and Components Classification Macro-categories, which identifies all categories of materials and components present in the monitored subject, as well as extends the future scope by including construction, technology, and material categories recurring in public social housing in the 20th century. The elements are arranged in a hierarchical tree within which it is possible to navigate to the lowest element of detail. Relative to materials and with reference to the pilot case of Via Alberto Mario there are actual data (i.e., diagnostic campaign), in addition to statistical data, there is a special section with related documentation.

The machine learning phase (Croce et altri, 2021), data integration and access through the InSPiRE platform were implemented according to a predictive approach through the enhancement of three-dimensional data obtained from laser scanning survey.

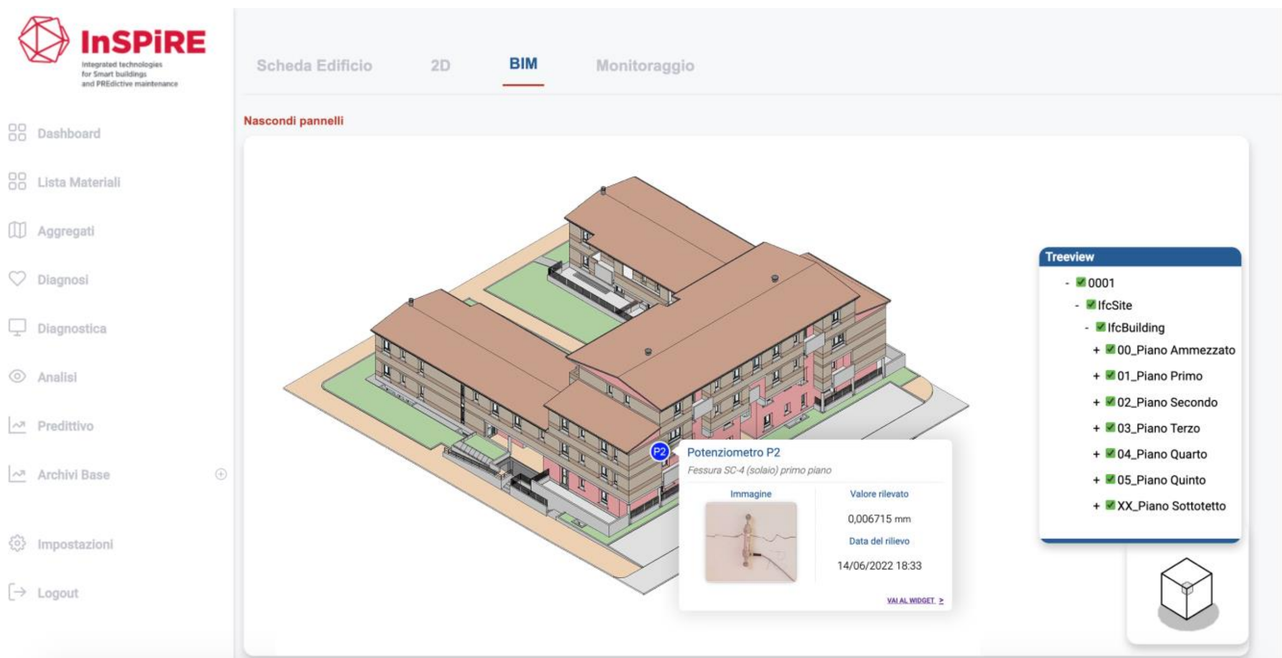

Figure 3. Data visualization in the BIM environment.

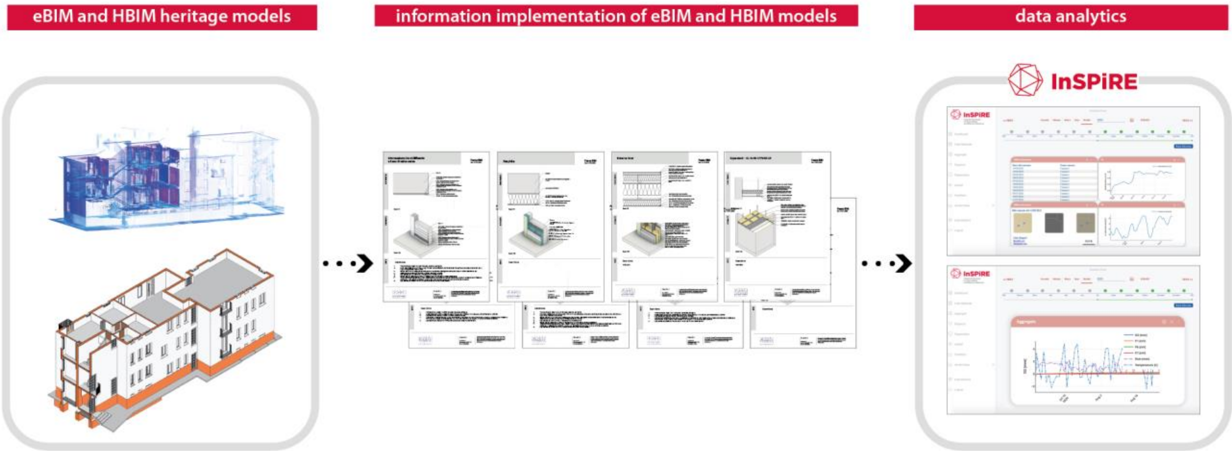

Figure 4. From 3D data modeling to data visualization.

Information characterized by increasing completeness was included in order to provide a flexible and scalable platform on contexts with varying data sources: general details on the survey, upload of 2D elaborates, as well as implementation of the digital twin according to BIM approach for complete archiving of all information. This model, intended to be queried directly by the platform, has been enriched with the data related to the sensors composing the acquisition system (i.e., type, qualitative characteristics, location within the building), from which it is possible to access the report files, the results produced by the data processing system, as well as the images recorded by the acquisition system. The satellite radar data, on the other hand, can be accessed from the platform as an additional layer to the spatial mapping, and not within the BIM model, from which point information of ground displacement, areal interpolation of ground displacement, and isoline representation can be displayed. In addition, a predictive algorithm has been developed that is useful for predicting and comparing different scenarios for improving the energy performance parameters of buildings, obviating as far as possible the inhomogeneity of available information. For the determination of the current state of the individual building and its energy profile, data calculated by analytical modeling of the building's behaviour were used where available, while for buildings lacking this, parametric indicators were used, assigning these indices based on the building's geometry, type and era of construction. This made it possible to describe the energy profile of all buildings in the Emilia-Romagna region's social housing stock, regardless of how the input data were sourced. In parallel, a set of recurring building energy efficiency improvement solutions was defined and standardized, with increasing levels of performance. The interventions are classified in relation to the technical elements involved and cover two levels of upgrading the building-type: a "typical upgrading," through the application of commonly used solutions, and an "advanced upgrading," through the introduction of interventions that reflect the best available technologies. Parametric cost indicators and achievable performance improvement indices are then associated with each standardized intervention, from which the expected reduction in operating energy costs is derived. This phase is central to the integration of the predictive diagnostics tool within the platform, as it allows a comparative evaluation of building performance improvement scenarios to be conducted, proceeding iteratively and in real time, in order to identify the solution judged most appropriate, also in relation to the cost-benefit index aimed at being achieved.

3.3 Machine learning and data visualization

In the period under study, monitoring activities of parameters such as: crack opening, accelerations, wall rotations, temperature, etc., continued within the analyzed case study. The collected data were analyzed in order to assess the most significant correlations between changes in the monitored parameters and seasonal variations or other events or interventions that may have determined them. Parallel to the collection of in-situ data, a finite element model of the building under study was constructed and nonlinear analyses were carried out in order to study in more detail the behaviour of the building subject to bottom failures.

In order to obtain a model for damage estimation on the existing social housing stock of the Emilia-Romagna Region, an analytical model was then developed, based on subsidence data provided by the Emilia-Romagna Region and the assumption of equivalent beam behaviour of the buildings. This analytical model allows, through the inclusion of a limited number of parameters and building data, to provide an initial estimate of the expected damage. From the data obtained on some representative buildings of social housing stock of the Emilia-Romagna Region, some damage classes have been defined, which are intended to guide engineers in prioritizing intervention and maintenance actions on the buildings. For the purpose of defining and validating predictive maintenance algorithms, an investigation methodology was then proposed, having the objective of identifying, at the territorial scale, the buildings most at risk and, on these, envisaging the installation of specific monitoring systems, starting from the prototypes developed within the project, depending on the damage mechanisms identified on the individual building. Through monitoring and thanks to the possibility of accessing the data collected through the InSPiRE platform, it will therefore be possible for technicians to identify situations of particular concern, on which to intervene in a preventive manner. Similarly, data acquired from optical sensors placed under continuous monitoring for about two months were processed. The acquired images were processed with Machine Learning and image processing algorithms, through Python, R, and Scala, in order to create a crack framework analysis workflow that was semiautomated and based on open-source tools.

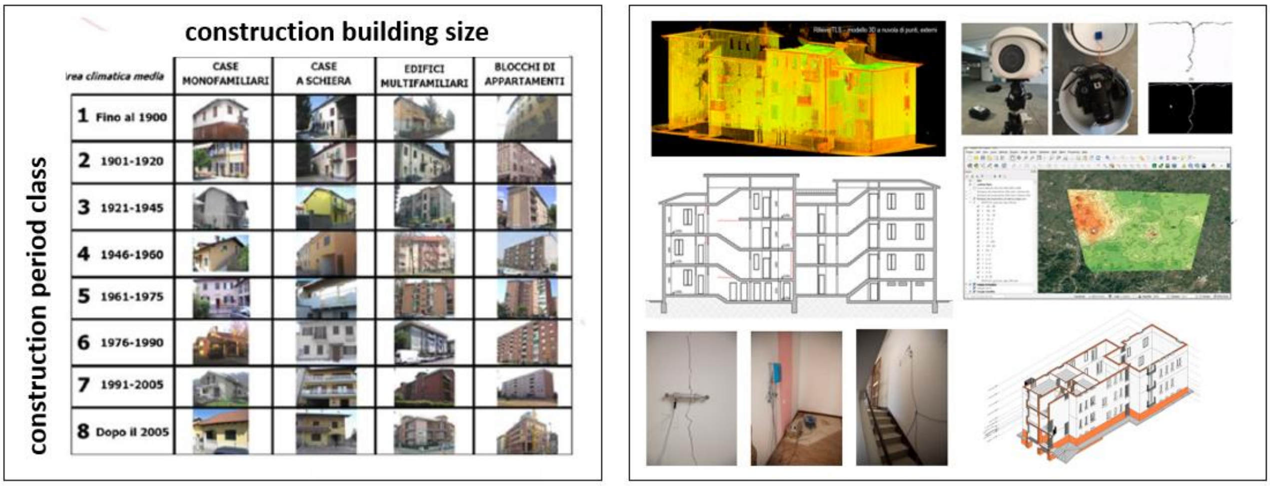

Figure 5. Comparison of data source types of the expeditious and non-expedient approach for defining the calculation algorithm.

After input, events pass through one or more stream processors, which may route the data (e.g. to storage) or perform analysis and other types of processing. Wording of event data to secure offline storage for batch analysis.
Critical Path Analysis, which analyses the flow of (near) real-time events to detect anomalies, recognise patterns based on recurring time intervals or trigger alerts when a specific condition occurs in the flow.
Handling of special types of non-telemetry messages from devices, such as notifications and alarms. The device registry is a database of provisioned devices and includes device IDs and generally device metadata such as location. The provisioning API is a common external interface for provisioning and registering new devices. Some IoT solutions allow command and control messages to be sent to devices.
In particular, the tests carried out on the case studies analysed highlighted an approach that has the potential to monitor changes in crack structure with sub-millimetre accuracy, in an indoor application context and under unchanged and favourable lighting conditions. The methodology requires an initial intervention by the skilled operator who must identify on an initial image the cracks of interest, then the method automatically segments all images by searching for cracks and identifying them. The comparison of several images allows the crack to be monitored.
Visualization of the images produced by monitoring through optical sensors and the results of data processing through the implemented algorithms is implemented in the InSPiRE platform in the BIM environment.
Finally, but not least, the research was directed toward the development of a predictive algorithm useful for predicting and comparing different scenarios of improvement in the energy performance parameters of buildings, obviating as far as possible the inhomogeneity of available information.
For the determination of the current state of the individual building and its energy profile, data calculated through analytical modeling of the building's behaviour (e.g., Energy Performance Certificates (D.L. 63/2013) were used, where available, while for buildings lacking them, parametric indicators were used, drawn from authoritative references taken from the technical literature, assigning these indices based on geometry, type, and era of construction of the building. This makes it possible to describe the energy profile of all buildings in the park, regardless of how the input data were sourced.

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Parametric cost indicators and achievable performance improvement indices are then associated with each standardized intervention, from which the expected reduction in operating energy costs can be derived. In this way, these assumptions can constitute a starting layout from which it will be possible to implement an initial comparison between the achievable performance after the improvement intervention and the original performance. This phase constitutes the core of the predictive diagnostics tool, since it allows to conduct a comparative evaluation of the building performance improvement scenarios, proceeding iteratively and in real time, in order to identify the solution judged most appropriate, also in relation to the cost-benefit index aimed at achieving.

3.4 Medium and long-term fallout

In later stages of development, the implementation of additional integrated machine learning and BIM-blockchain modules is planned. Indeed, the scalability of the outcomes of the research conducted so far makes it possible to transfer and implement the approaches and protocols tested to similar cases of built heritage. In fact, the choice to operate the experimentation on examples of 20th-century social housing is closely linked to the technological and construction characteristics of the heritage examined, as well as to the specificities of the end users who inhabit it. Urban regeneration and social regeneration are, as well expressed by European policies, indispensable phenomena in order to develop strategies for the management, maintenance and reconversion of the built heritage.
However, it is necessary to foster, with reference to the objectives described above, the propensity of organizations, actors and in general the value chain of the intervention on the existing built heritage, to manage cloud-computing solutions, as well as to adopt order management and operational models oriented to the systematic collection of data, Bigdata, become

essential requirements to implement the analytics functionalities and Iot integrations foreseen (Campos, 2020).
The challenge of the near future is therefore the training of machine learning functionalities in order to test their effectiveness with reference to case studies considered representative of areas of management and maintenance, ordinary and extraordinary, of the built environment. Experiments that will be conducted finally with reference to policies supporting interventions to improve the energy performance and safety of the built heritage in order to verify their effectiveness in operational terms.

4. CONCLUSIONS

The integration of key enabling technologies for the implementation of data sharing and visualization platforms aimed at the management of intervention on the existing built environment and the maintenance, including predictive maintenance, of the built heritage can contribute greatly to the digitization processes of the supply chain.
However, barriers to the introduction of the technologies under consideration persist. On the one hand, the evolution of technologies for the management, modeling and use of Big Data now makes the application of machine learning approaches accessible, through specialized skills, even to the construction sector, which has historically been resistant to the introduction of higher levels of industrialization. On the other hand, the resistance of supply chain actors to the application of a typical Open Data approach as well as to greater knowledge sharing and transparency of the entire life cycle of the work remain the main barriers to the wider dissemination of the methods and protocols under consideration.
However, there is a growing interest, also on the part of the public operator, in the experimentation and sharing of good practices that can make possible the transfer of methods and approaches to a more objective management of the issues related to the intervention on the existing. traditional methods of inspection and monitoring of the state of preservation and operation of materials, components and building systems is not only not objective, but is no longer sustainable in terms of time, cost and probability of error related to the established experience of the operator in charge of inspection, monitoring and diagnosis operations.
Similarly, and with reference to the social housing case studies examined, the technological fragility and together with the increase in social fragility related to the increasingly necessary building and urban redevelopment interventions not only on the national territory make it necessary to identify, test and validate multiscalar approaches. Scalability of innovation, together with the possibility of accessing dedicated resources on a competitive basis, remains, according to the authors, a central node in support of public-private supply chain digitization projects.

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