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Efficiency and Sustainability: The Role of Digitization in Re-Inhabiting the Existing Building Stock

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Abstract: Cities are complex and constantly evolving systems where changing social needs have always reshaped the built environment. Considering recent evolutionary trends in housing emergencies, amplified by the COVID-19 pandemic, and environmental sustainability goals, a rethinking of the building heritage is fundamental. This article aims to promote the conversion of buildings designed initially for nonresidential uses as a process and project strategy based on energy efficiency and a holistic and integrated vision of the circular economy. The methodological approach is based on two main phases: definition of evaluative parameters for the potential reuse of a building, and integration of the evaluation system in a BIM and GIS environment. The result is a tool for rapid automatic pre-evaluation of the potential conversion of a building into a residential space. Applying the developed methodology allows for a practical approach to the significant issue of sustainable construction, with particular attention to energy improvement and the reduction of environmental impact related to the construction of new buildings. The originality of the contribution lies in the systematization of various digital technologies to provide fundamental support for managing and transforming the varied and widespread unused real estate assets in a state of abandonment and degradation.

Keywords: adaptive reuse; multicriteria evaluation tools; building information modeling; geographic information system; building efficiency; energy savings; data analytics

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1. Introduction

Housing is not an object but a process that has developed over time and space [1]. The issue of housing has gone through different "building cycles" throughout history, determined by population growth and the evolution of economic models, ranging from the construction of large urban expansion districts to the recovery and redevelopment of existing building heritage. Housing, therefore, is an increasingly complex issue that requires a combination of social, environmental, and technological aspects to offer sustainable solutions that put humans at the center of transformations in the built environment.

The opportunity to have quality housing is one of the fundamental aspects of ensuring the quality of life of individuals and their social inclusion [2]. The housing emergency in Europe is a reality that many countries still face. According to data provided by the report "The State of Housing in the EU" by the Housing Europe Observatory, in 2017, 10.2% of households spent more than 40% of their income on housing expenses, and this percentage reached 37.8% among those at risk of poverty [3]. According to Eurostat, only 4% of the Italian population has access to subsidized housing, nearly one-third of tenants paying market rents were burdened by housing costs in 2017, and the rate of severe housing deprivation remains very high at 11.1% (compared to an EU average of 5.6%). (According to Eurostat's indicator, people who, in addition to living in overcrowded housing, have at least one of the following issues are considered to be in severe housing deprivation: lack of bathroom, shower, or indoor toilet; presence of damaged windows, doors, roofs, floors, or moisture; and poor lighting problems. Most homes in Italy are now equipped with indoor toilets (which is not always the case in some other European countries) but have greater issues with moisture or certain structural deficiencies, as well as insufficient space.) The European report emphasizes the need for significant investments to improve the quality and energy efficiency of the building stock and to increase the supply of public housing, addressing the phenomenon of illegal occupation and improving the management capacity of the buildings.

In Italy, the housing issue has remained on the sidelines of political agendas for a long time, both because of the high quantity of owner-occupied houses and because of an optimistic view regarding the reduction of housing poverty thanks to economic development. This did not happen, and the issue has returned to the forefront due to the economic and financial crisis exacerbated by the epidemic crisis.

An analysis of the current building stock in Italy highlights the importance of reflecting on the adaptive reuse of buildings that are in a state of abandonment and its potential to respond to the housing emergency amplified by the COVID-19 pandemic, as well as to energy efficiency needs, in line with the European Clean Energy Package and national objectives for emissions reduction, following the "no net land take" paradigm [4].

The UNI 10914-1:2001 standard defines reuse as a "combination of all the decisions resulting from analytical activities aimed at changing the use of a building or its spatial areas, or, if not in use, defining its use. Reuse can also be implemented without building works, or with maintenance, redevelopment or restoration interventions."

Adaptive reuse refers to the "reuse of a building or structure to give it new life through a new function" [5]. In the 19th century, the architect Eugène Emmanuel Viollet-le-Duc developed a theoretical approach to adaptive reuse to preserve historical monuments. Viollet-le-Duc [6] argued that "the best way to preserve a building is to find a use for it and then to satisfy so the needs dictated by this use that there will never again be any need to make further changes to the building" [7].

The potential benefits of adaptive reuse are highlighted in the European directive "Adaptive Re-use of the Built Heritage: Preserving and Enhancing the Values of our Built Heritage for Future Generations," adopted on 23 November 2018 in Leeuwarden as part of the European Year of Cultural Heritage initiative "Heritage in Transition."

The directive defines adaptive reuse as a strategy to preserve those elements that contain cultural, historical, spatial, and economic values while simultaneously adapting the place to new uses. The new functions are thus combined with the heritage values in an active and meaningful dialogue [8].

The key reading offered by the European directive is to consider the built heritage as an artificial landscape that can be reworked and reshaped when necessary, starting by analyzing social, cultural, environmental, and economic needs. There are numerous examples of adaptive reuse in the literature and various methods for evaluating the potential transformation of a building for residential purposes.

It has been successfully applied to many types of structures, including airports [9], churches [10], schools [11], offices [12], government buildings [13], and industrial buildings [14].

Around the world, this strategy is considered fundamental for sustainable development, with major applications having been carried out, especially in Australia [15–17], Canada [18,19], Hong Kong [20–23], the United States [24], North Africa [25], and Europe [26].

In Italy, among the most emblematic examples of existing buildings converted into residences are the Murate in Florence [27], the Ex Tobler in Turin, and the Galfa Tower in Milan [28]. The Murate convent, built in the 15th century and later used as a male prison complex, underwent adaptive reuse from 1997 to 2014 to create a functional mix that includes social housing, commercial areas, and offices.

Ex Tobler is a recovery and transformation project of an industrial building from 1907 into a complex used for housing, offices, and commercial spaces; the project won the "Architetture Rivelate" award in 2012. This intervention's "winning" strategy consists of the definition of medium-small housing units, unfinished to guarantee customization of the spaces, except for the provision of a bathroom and kitchen.

Torre Galfa, built between 1956 and 1959 according to the design of architect Melchiorre Bega, was originally built to house the offices of the Sarom company. After being abandoned in 2001, a renovation and conversion project was launched by architect Maurice Kanah of the BG&K Associati Studio, which made it possible to restore recognizability to the building through a mix of residential, hotel, and commercial functions.

This trend allows for effectively extending the useful life of existing buildings by making them more efficient, and, compared to new constructions, it involves lower costs in terms of materials, energy, and pollution [29]. Therefore, adaptive reuse can be considered a key element to support sustainable development and urban resilience [30] through the energy efficiency of buildings.

The promotion of energy efficiency is fundamental as the building sector is one of the most environmentally impactful sectors; in fact, according to EU estimates, buildings are responsible for 40% of global energy consumption, 36% of greenhouse gas emissions, and 35% of total waste produced, and they require about 50% of resources [31]. Energy consumption in construction is closely related to the usage phase of buildings [32], which requires high energy consumption for winter and summer conditioning and lighting [33], but also to the production of building materials. In this context, adaptive reuse represents an effective strategy to improve the sustainability of existing buildings [34], a valid alternative to demolition and reconstruction, capable of generating new cultural, economic, and social values, supporting and promoting innovative dynamics of local development [35]. Adapting and reusing an existing building can often be faster and more cost-effective than demolishing an old building, followed by subsequent reconstruction [36].

The sustainable and circular reuse of spaces and buildings also responds to the sustainable development goals promoted by the Agenda 2030, in particular, SDG 11 "Make cities and human settlements inclusive, safe, resilient and sustainable"; SDG 15 "Protect, restore and promote sustainable use of terrestrial ecosystems"; and SDG 7 "Goal 7: Sustainable, affordable and modern energy systems for all." It also aligns with the "Roadmap to a Resource Efficient Europe," which sets a goal of zero consumption of new land by 2050 [37].

The current challenge is to identify the most suitable ways to change the intended use of a building, extend its useful life, and adapt the interior space to new ways of living that require greater flexibility. Therefore, tools are needed to assess the potential adaptive reuse of existing buildings, which can support a rapid selection of the most suitable ones.

The preliminary evaluation of the potential reuse of an existing building falls under the comparative pre-diagnostic activities aimed at identifying its performance in the first analysis to decide if it is adaptable to residential use without radical modification interventions. Using the performance criterion allows for defining the conditions of the context, the state of conservation, and the usability of a building, considered to be suitable indicators to define its "reuse potential."

The definition of evaluation parameters to verify the pre-feasibility of converting disused buildings into residences stems from a study of the main tools and evaluation systems in the literature related to adaptive reuse and redevelopment interventions, such as the Score-Based Pre-diagnostic Activity Method—MAPP [14].

Many scholars internationally have developed evaluation tools such as the Transformation Meter and the Adaptive Reuse Potential (ARP) model.

The first model was developed by Rob P. Geraedts and Theo van der Voort and applied to vacant office buildings in a particular area of Rotterdam. The Transformation Meter consists of a series of checklists developed based on interviews with the local population, through which it is possible to evaluate the potential for transforming office buildings into housing. The methodological approach developed in this study involves five main phases: inventory of available vacant offices on the market, evaluation with "veto criteria," evaluation with gradual criteria, determination of the transformation class, and detailed evaluation of the transformation potential.

The factors considered relate to both the building and the urban context in which it is located. The criteria for evaluating the building include the year of construction, the main dimensions, the state of conservation, the level of acoustic insulation, the possibility of expansion, the air and light ratio, the possibility of creating secure entrances, and the presence of hazardous materials. At the urban scale, the parameters relate to distances from major services (2 to 5 km) and noise and air pollution.

The *Adaptive Reuse Potential* model was developed by Craig Langston [38]. It is a generic model that can be implemented and applied to all types of buildings in all countries; it is based on a mathematical formula that estimates the physical life, evaluates seven rates of obsolescence (physical, economic, functional, technological, social, and legal), and calculates the useful life and the potential for adaptive reuse of a building. With this tool, an index of the reuse potential is calculated and expressed as a percentage, and existing buildings can be classified based on this factor.

Both of the adaptive reuse evaluation tools described above do not involve the use of digital technologies. Current approaches to support the design, planning, and execution of projects with Building Information Modeling (BIM) allow for defining and evaluating environmental issues and potential improvements of a particular object of study (product, building, etc.) and selecting alternative solutions [39], but they are still not widely used to support adaptive reuse interventions [40].

Building Information Modeling is defined by the National Institutes of Buildings as "a digital representation of the physical and functional characteristics of an object" [41].

BIM is based on a technology that incorporates into a three-dimensional geometric model the necessary information required by the Architecture, Engineering, Construction, and Facility Management (AEC/FM) sector [42].

The diffusion of BIM in Italy is promoted by the regulations that regulate "specific electronic modeling methods and tools for construction and infrastructure," introduced into Italian legislation with art. 23 of Legislative Decree no. 50 of 2016 (Code of Public Contracts) and subsequently detailed with DM 560/2017. The latter has introduced its gradual mandatory use for public contracts by establishing timing and methods for creating a digital environment for organized collection and sharing of information related to work.

Zainudin et al. explore Building Information Modeling used to analyze traditional Malay houses' building and environment performance in an adaptive reuse experiment project [43]. Autodesk Green Building Studio is the BIM software used to analyze building performance. It allows one to run building performance simulations to optimize energy efficiency and to work toward carbon neutrality earlier in the design process, but it needs to allow the compatibility of the building with adaptive reuse to be quickly assessed.

The main contribution of this study is developing a methodological framework for an integrative BIM-GIS (Geographic Information System) approach to assess the feasibility of adaptive reuse projects for residential purposes and to promote the transition toward a circular economy.

GIS is defined by Burrough as "a powerful set of tools for collecting, storing, retrieving at will, transforming and displaying spatial data from the real world" [44].

The proposed research was developed within the framework of an agreement for research activities in the knowledge, maintenance, and enhancement of the real estate/architectural heritage owned or managed by the Territorial Companies for the Residential Building of Rome. The agreement includes a gradual organization and digitization of the real estate assets according to BIM-oriented processes, methods, and tools to effectively address the important issue of sustainable construction, with particular attention to the energy improvement of buildings.

The originality of the contribution lies in the systematization of different digital tools to perform a rapid automatic assessment to compare the adaptive reuse potential of different buildings and guide the recovery and enhancement interventions of the existing building heritage.

2. Materials and Methods

Adaptive reuse is a consolidated technique to create new spaces by properly selecting existing buildings to convert and reuse. From a territorial regeneration perspective, the decision-making process for activating adaptive reuse initiatives is crucial, as determined by the growing number of actors and new relationship systems. It is a complex process that requires a clear understanding of determining the most appropriate future for a building in a particular place and time [45].

Each adaptive reuse process can be set up by considering some essential steps:

- Building analysis (original function, geometric, material, structural analysis, etc.);
- Definition of actors (future users, investors, control authorities, etc.);
- Definition of actions (maintenance, recovery, restoration, consolidation, etc.);
- Definition of impacts (environmental, cultural, economic, physical, functional, social, etc.).

Based on these considerations, a BIM and GIS-based evaluation tool is proposed within the framework of building analysis to support the management and conversion processes of existing building stock that is abandoned or in a state of degradation. This tool is based on a list of indicators that concern both the urban and building scale, aimed at evaluating the suitability of buildings to be transformed and reused as housing.

The methodological approach adopted for the definition of this tool is based on 2 main phases:

1. Definition of performance indicators for a multicriteria evaluation approach aimed at assessing the potential conversion of a building for residential purposes;
2. Integration of the evaluation system in the BIM/GIS environment for automatic verification.

2.1. Definition of Parameters for Evaluating the Potential for Adaptive Reuse of a Building and the Feasibility of Transforming It into a Residence

A reuse project involves estimating the residual performance of a property or its parts based on the requirements of the new intended use.

The factors that make a property more or less suitable for residential use are numerous and varied, including economic, environmental, social, legal, and regulatory aspects. In this article, such factors will not be addressed as a specific method is proposed to analyze performance aspects strictly related to the construction characteristics, preservation condition of the buildings, and the urban context in which they are located through the use of the latest digital technologies.

For the development of the proposed method, indicators concerning both the building and the urban context in which it is located have been selected. These allow for the automatic verification of aspects related to the physical and technological feasibility of adaptive reuse interventions in a BIM and GIS environment.

The selected indicators are easily interpretable by technicians and public administration operators, measurable, updatable, and based on standards recognized by the scientific community. The evaluation of the building organism concerns both the technological and environmental-spatial systems.

The parameters selected for the pre-feasibility check are based mainly on the following:

- Sanitary requirements provided for residential buildings, whose main reference standard is the ministerial decree 5 July 1975 “Modifications to Ministerial Instructions 20 June 1896, Regarding the Minimum Height and Main Sanitary Requirements of Dwelling Rooms”;

- Technical prescriptions necessary to ensure the accessibility, adaptability, and visitability of private and public residential buildings to overcome and eliminate architectural barriers, provided by DM 236–14 June 1989;
- UNI 11150-1:2005 standard, Construction, qualification, and control of the building project for interventions on the built environment: General criteria, terminology, and definition of the preliminary document for design, point 3.3 and UNI 11150-3:2005, Construction, qualification, and control of the building project for interventions on the built environment: Analytical activities for interventions on the built environment, point 3.1;
- Performance indicator on distance from services and public transportation for evaluating the environmental sustainability of residential buildings provided by the ITACA protocol, updated based on the UNI/PdR 13.1:2019 reference practice.

The identified parameters allow for examining and measuring the performance of existing building systems, their components, and the spaces that constitute them.

The evaluation is articulated on five main performance areas:

- Safety;
- Well-being;
- Usability and adequacy;
- Energy efficiency;
- Site quality.

Each area has identified categories that address specific aspects and threshold values (Table 1).

Table 1. Evaluation parameters for assessing the potential adaptive reuse of a residential building ("Radical interventions" refers to works and modifications necessary to replace even structural parts of buildings, with possible alterations of volumes and surfaces.) (Source: elaboration from [46]).

Area	Category	Performance Indicator	Threshold Value	Threshold Value Verification	Outcome of Verification with Negative Threshold Values
Safety	Functionality of reinforced concrete structures	Columns and beams with exposed reinforcement bars with deformations or presence of corrosion.	Absence Presence	Positive Negative	Not suitable for adaptive reuse
		Vertical cracks and fissures present in the central part of reinforced concrete beams and/or diagonal cracks and fissures in the beams near the supports on the columns.	Absence Presence	Positive Negative	Not suitable for adaptive reuse
		Vertical fissures present on the columns that are parallel and repeated, even of small thickness.	Absence Presence	Positive Negative	Not suitable for adaptive reuse
		Diffused cracks in the partitions and significant sinking in the floors.	Absence Presence	Positive Negative	Not suitable for adaptive reuse

Table 1. *Cont.*

Area	Category	Performance Indicator	Threshold Value	Threshold Value Verification	Outcome of Verification with Negative Threshold Values
	Functionality of non-reinforced concrete structures	Diagonal lesions in walls with a thickness greater than or equal to 25 cm.	Absence Presence	Positive Negative	Not suitable for adaptive reuse
		Bulges on load-bearing masonry accompanied by vertical lesions.	Absence Presence	Positive Negative	Not suitable for adaptive reuse
		Lack of mortar and bricks.	¼ of the thickness of the walls.	<Positive ≥Negative	Not suitable for adaptive reuse
		Lowering of arches and vaults in the central part.	5 cm	<Positive ≥Negative	Not suitable for adaptive reuse
		Outward leaning on walls where arches or vaults rest.	4 cm	<Positive ≥Negative	Not suitable for adaptive reuse
		Broken wooden beams.	Absence Presence	Positive Negative	Compatible with radical interventions
	Roofing made of wood	Pitched roof with wooden structure without ties and with out-of-plumb walls with damage on the top floor or under the eaves.	Absence Presence	Positive Negative	Not suitable for adaptive reuse
		Pitched roof with wooden structure with broken main beams.	Absence Presence	Positive Negative	Compatible with radical interventions
		Pitched roof with wooden structure with breaks in the joints between the beams.	Absence Presence	Positive Negative	Compatible with radical interventions
		Infestation of insects or fungi.	Absence Presence	Positive Negative	Compatible with radical interventions
	Safety in use	Presence of asbestos.	Absence Presence	Positive Negative	Compatible with radical interventions
		Vertical connections: Staircase–ratio between rise (a) and tread (p).	2a + p = 0.63 m	<Negative ≥Positive	Compatible with radical interventions
		Vertical connections: Staircase–ramp width.	0.80 m	<Negative ≥Positive	Compatible with radical interventions
		Vertical connections: Staircase–landing size.	every 15 steps	≤Positive >Negative	Compatible with radical interventions
		Height of window or balcony railings, stairwells, walkways, mezzanines, etc.	1 m	<Negative ≥Positive	Compatible with minimal interventions
		Vertical connections_ Elevator.	Absence Presence	Negative Positive	Compatible with radical interventions

Table 1. *Cont.*

Area	Category	Performance Indicator	Threshold Value	Threshold Value Verification	Outcome of Verification with Negative Threshold Values
		Vertical connections: Elevator–minimum cabin dimensions to allow use by a person in a wheelchair.	1.20 m deep and 0.80 m wide	<Negative ≥Positive	Compatible with radical interventions
		Vertical connections: Elevator–clear door opening on the short side.	0.80 m	<Negative ≥Positive	Compatible with minimal interventions
Well-being	Bright	Illuminated surface area.	1/8 of the floor area	<Negative ≥Positive	Compatible with radical interventions
	Thermo-hygrometric	Thickness of perimeter wall.	0.30 m	<Negative ≥Positive	Compatible with minimal interventions
Usability and suitability	Habitable condition	Minimum internal height 2.7 m	80%	<Negative ≥Positive	Compatible with radical interventions
	Accessibility	Entrance level difference	3.20 m	≥Negative <Positive	not compatible
		Access door–useful passage width (UPW)	0.90 m	<Negative ≥Positive	Compatible with radical interventions
		Access door–depth of the area in front/behind	1.50 m	<Negative ≥Positive	Compatible with radical interventions
	Equipability	Possibility to install an elevator in the stairwell without compromising the usability of the ramps and horizontal landings, especially in relation to the need to ensure adequate flow in case of emergency evacuation–cabin and stair size	1.20 m depth and 0.80 m width 0.80 m width of the ramp	<Negative ≥Positive	Not suitable for adaptive reuse
	Adaptability/Flexibility	Possible reconfiguration of interior space–structural grid	3.6 m	≤Negative > Positive	Not suitable for adaptive reuse
Energy Efficiency (Source Energy Efficiency Analysis: [47])	Volume-to-Area Ratio	RC = $(6V)^{2/3} A^{-1}$	0.75	<Negative ≥Positive	Not suitable for adaptive reuse
	Renewable Energy Production (Roof Area)	RS (roof shading) = As/Atot Shaded roof area over total roof area	0.3	≥Negative <Positive	

Table 1. *Cont.*

Area	Category	Performance Indicator	Threshold Value	Threshold Value Verification	Outcome of Verification with Negative Threshold Values
Site quality	Setback distances from infrastructures and easements to be considered outside urban areas (Art. 338 of Legislative Decree no. 1265/193)	Buffer zone for cemeteries, measured from the cemetery's enclosing wall	200 m	<Negative ≥Positive	Comparative parameters
	Distance from services	Buffer zone for railways	30 m	<Negative ≥Positive	
		Buffer zone for airports	300 m	<Negative ≥Positive	
		Buffer zone for wastewater treatment plants	100 m	<Negative ≥Positive	
		Neighborhood businesses	1 km	≥Negative <Positive	
		Bars, restaurants, pizzerias. . .	500 m	≥Negative <Positive	
		Banks and post offices	2 km	≥Negative <Positive	
		Basic medical services (pharmacy, general practitioner)	5 km	≥Negative <Positive	
		School buildings	2 km	≥Negative <Positive	
		Sports centers	2 km	≥Negative <Positive	
	Distance from public transportation	Railway station	2 km	≥Negative <Positive	
		Bus, metro, tram stops	1 km	≥Negative <Positive	

In the "Safety" area, given the aim of speed in applying the proposed methodology, only endogenous risk indicators have been considered, i.e., easily visible signs attributable solely to the peculiarities and conditions of the evaluated building.

The "Well-being" evaluation area concerns both luminous and thermo-hygrometric habitability, which also influences the energy efficiency of the building.

The "Usability and adequacy" area of spatial dimensionality-geometry allows for evaluating the aspect related to overcoming architectural barriers and the flexibility of the environment, which depends mainly on the construction system and, in particular, on the measures of the building's structural grid [14].

The "Energy efficiency" area allows for assessing the potential related to the energy performance of the building envelope and the integration of renewable energy source production systems.

At the urban scale, in the "Site quality" area, the aspects being verified are the distances from the main services and the quality level of the context.

Unlike the previous evaluation areas, "Site quality" provides exclusively comparative parameters verifiable through GIS technology.

The evaluation of each indicator allows for determining whether the building meets the following:

- Not suitable for adaptive reuse;
- Compatible with radical interventions;
- Compatible with minimal interventions.

Some performance indicators have been selected, the positive outcome of which is of fundamental importance for verifying compatibility.

2.2. Verification of Evaluative Parameters in the BIM-GIS Environment

The use of Building Information Modeling to improve the efficiency and sustainability of the entire design and construction process is becoming an increasingly consolidated reality. The potential of BIM to promote a transition toward a circular economy is still an area of research in its infancy [44].

The methodological approach adopted to automate the preliminary verification process of the feasibility of adaptive reuse projects for residential purposes in the BIM-GIS environment involves three main phases:

1. Quick survey of the building;
2. Building modeling in the BIM environment;
3. Automatic verification of evaluation parameters in the BIM and GIS environment.

2.2.1. Rapid Survey of the Building

The first phase involves acquiring buildings' main dimensional, functional, and technological information through an indirect survey, which refers to a technique of surveying that does not involve direct measurement of the object or area's dimensions or characteristics.

To acquire geometric data and subsequently create 3D models, reality-based digital survey techniques can be employed, classified as techniques based on passive sensors (image-based methods) and techniques based on active sensors (range-based methods) [48].

The first type of survey is based on the exploitation of the light present in the environment to obtain images from which 3D information can be extracted later; photogrammetry is among the best-known image-based methods. Photogrammetric surveying uses mobile devices, particularly smartphones, which provide 3D point clouds [49].

Images can also be acquired using, where possible, remotely piloted aircraft—UAVs.

The second type of survey is based on active sensors that emit an electromagnetic signal recorded by the instrument to determine the distance measurement. Laser scanners are among the most commonly used range-based tools in the architectural field [50]. Light Detection and Ranging (LiDAR) technology, also currently integrated into the latest mobile devices, allows for quickly acquiring large amounts of 3D data, which requires further editing work to create the geometric model.

The resulting point cloud can be further post-processed to create a Building Information Model [51], which describes the relational characteristics and attributes of the building elements.

2.2.2. Modeling the Building in a BIM and GIS Environment

The digital tools used in the BIM environment support the sharing and integration of different skills, allowing for a holistic view of the entire building process. This methodology allows for optimizing resources, testing different efficiency solutions, carrying out simulations and precise material calculations, and minimizing errors in the design phase thanks to verifying interferences, reducing time and increasing the quality of the process. The BIM methodology can also be applied to existing building stock [52].

The BIM implementation process is based on the correct graphical representation of architectural components identified as parametric objects in the model, which can be mapped through advanced 3D survey techniques.

Therefore, we are talking about real-based modeling, and the model must include all the information related to geometric consistency, morphology, and material-construction characterization.

The digitization process includes several stages to reach the final model, from identifying the construction details of the building stock to defining data collection procedures, modeling information in 3D, treating parametric components/objects, to creating the BIM as built. This presupposes collecting a specific amount of information whose level of detail is functional to the objective, the degree of knowledge to be reached, and the nature of the building, and it depends on the availability of existing data and documentation.

The model information that allows for subsequent verification of compatibility with adaptive reuse interventions mainly concerns maintenance conditions and the dimensions of technical elements and environmental units, the building's position, orientation, and compactness.

The *Level of Development* 300 of the BIM model enables the application of automatic checks through specific algorithms developed with Dynamo.

Once the as-built model is completed, it is essential to generate the table of room dimensions, which allows extracting the actual dimensions of each real room in rows and columns to initiate a complete verification through an algorithm.

As for the table of the surface area referred to the roof, it is essential to verify the actual dimensions of the roof and evaluate the possibility of installing solar systems such as photovoltaic panels. The generation of this table, along with the other tables related to the rooms, provides a complete view of the building's dimensions and initiates a complete verification through specific algorithms. In particular, the table of the roof surface area allows for a clear and precise extraction of the roof's dimensions so that the available surface area for the installation of solar panels can be calculated and verified that there are no obstacles, such as trees or surrounding buildings that could create shadows and reduce the system's efficiency.

The building can be imported into InfraWorks Software to analyze, plan, and manage roads and other infrastructure in the surrounding area. The Revit geometry is geographically positioned and imported into the InfraWorks model.

InfraWorks allows objects to be located in space, linked to specific alphanumeric attributes stored in the relational database (Archive), and managed as "informational layers" that identify their spatial relationships. The visually realistic and detailed models are built using all available GIS data: environmental and anthropic data, orthophotos, terrain models, and survey data, allowing for a more in-depth analysis of real estate and the surrounding environment. Additionally, adding the model to InfraWorks allowed for verifying any obstacles, such as buildings or trees near the studied property, that could create shadows and reduce the efficiency of photovoltaic systems. This operation made it possible to ensure optimal coverage and to maximize energy production.

2.2.3. Verification of Evaluation Parameters in the BIM and GIS Environment

The BIM approach to the construction process methodology allows for creating an informative model of the building that can be queried, which is fundamental for carrying out specific verifications and analyses [53].

The flowchart of the connection of the BIM model with digital technologies is shown in Figure 1.

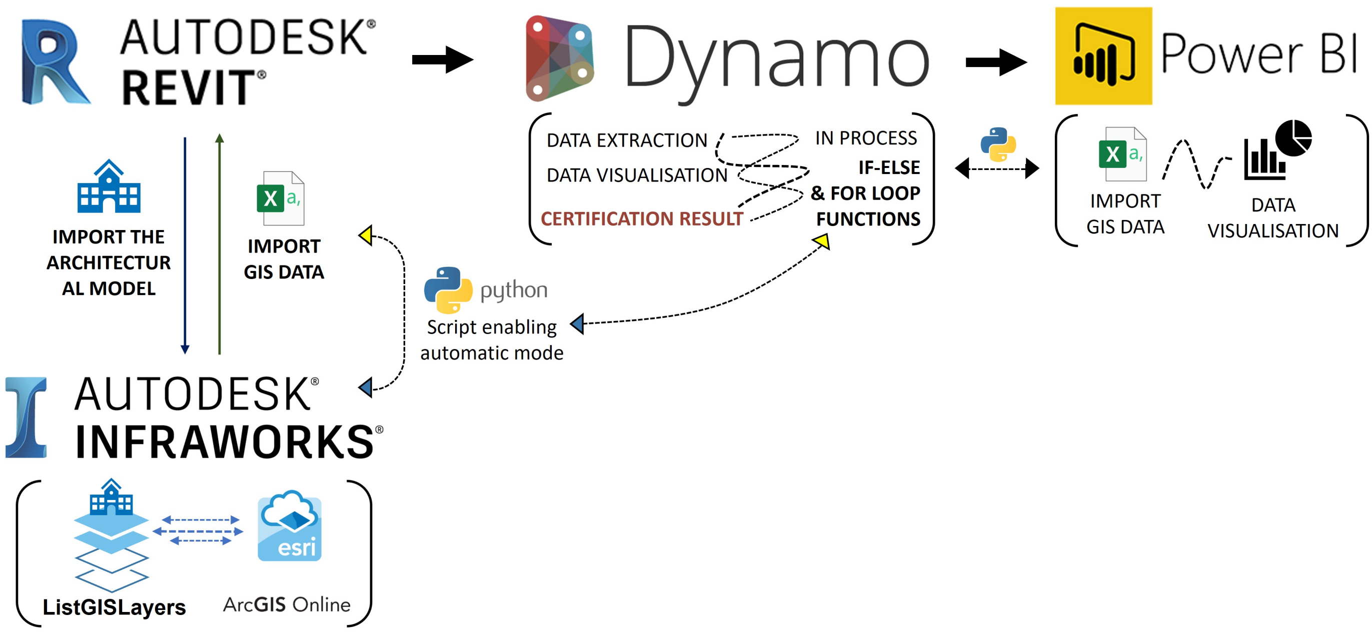

Figure 1. Flowchart of the connection of the BIM model with digital technologies.

The open-source visual programming tool Dynamo was used to automatically verify indicators capable of outlining the adaptability of a building for residential adaptive reuse.

Dynamo is a tool based on Visual Programming Language (VPL), an operational mode that does not involve digitization of code lists but manipulation and connection of graphical entities (nodes) to perform analysis or generate algorithms that represent a logical workflow.

The nodes perform specific individual operations, receiving data of the exact nature of the upstream node through a horizontal connection that establishes the logical flow between one node and another.

The library in Dynamo offers a special section containing a series of nodes that allow the connection of categories, families, types, and instances present in the BIM model, developed through Revit software.

Through the visual programming software Dynamo, it was possible to create algorithms to query the building model created in the BIM environment and automatically fill in all the values of the identified evaluation parameter fields.

The logical flow involves three steps:

- Acquisition of data from the 3D model of the current state of the building;
- Formulation using the logic described by "IF-ELSE" rules to evaluate the level of suitability of the buildings, with the visualization of the result for each space;
- Formulation using the logic described by a "FOR loop" for calculating the percentage of positive thresholds and "IF-ELSE" logic for printing and checking the result of the compatibility of the performance indicators.

The evaluation of performance indicators related to "Site Quality" and "Energy Efficiency" requires using GIS technology, which can be carried out in GIS software and/or BIM software. The procedure can be manual or automatic.

In this study, the logical flow of an automatic solution was adopted, which required the following steps:

- Use of Autodesk's Python library, InfraWorksAPI, to extract GIS data from InfraWorks;
- Importation of the data into Revit;
- Automatic calculation of the distance of services from areas of interest for "Site Quality" and shading caused by trees or surrounding buildings of a certain height for "Energy Efficiency" within Revit.

The automatic export of data and importation into other technologies, such as Revit Software, allows for a comprehensive evaluation within a single environment, with a single algorithm applied to multiple areas and categories.

The results of the automated verification generated by the custom Dynamo node are directly transmitted to Power BI through a data connection configured to access the data generated by the custom node. Power BI offers the ability to configure a connection with various data sources, such as CSV files, Excel, relational databases, cloud services, and more. Once the connection is configured, the results can be displayed on the Power BI dashboard. Thanks to its ability to analyze real-time data and easily share information with other users, Power BI promotes a better understanding of the collected data and enables data-driven informed decision-making.

3. Case Study

The described methodology approach has been applied to a school located within the complex of the largest public assistance and charity institution in Rome, the Institute Romano San Michele, in the popular neighborhood of Tor Marancia within the administrative area Municipio VIII.

The three-story building was built in the early 1960s with an H-shape. The property can be accessed through three entrances, two of which are secondary and not accessible from the outside due to architectural barriers.

The interior spaces are designed for the strictly necessary purposes of school activity with well-distributed paths: it is possible to distinguish the spaces used as common classrooms at high heights and rooms used as restrooms.

The building comprises a concrete frame structure, with masonry infill with bricks arranged on four heads with a thickness of 70 cm.

It has a flat roof of concrete blocks and two terraces accessible from the third floor on both the east and west elevations. The central part of the complex is used as a very well-lit stairwell, thanks to two glass block windows that allow natural light to enter.

The external fixtures are made of iron, with single glass panes, and without sun shading. The building services are limited to the centralized heating system.

The property is currently in poor maintenance condition in many aspects.

From a building and system perspective, it needs significant maintenance; the structure is earthquake-resistant due to its location but needs a safety intervention.

The BIM model of a school has been developed and is detailed to a required 300 level of detail (LOD). The LOD 300 model presented in Figure 2 is found apt for the evaluating parameters of this study.

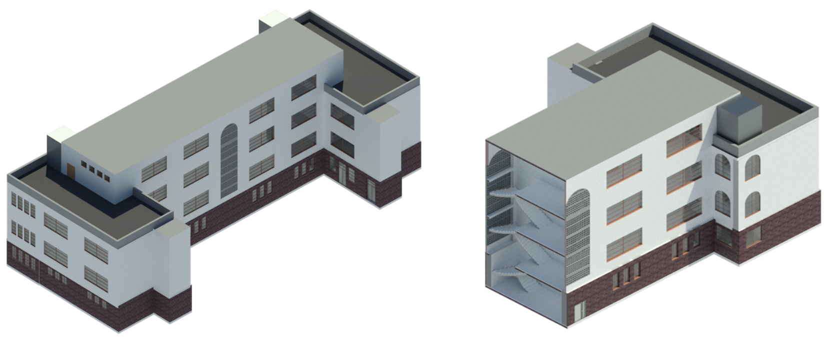

Figure 2. BIM model of the case study—the complex of the Public Institution of Assistance and Charity IPAB.

Automatic BIM Analysis Applied to the Case Study

As an example, the algorithm developed to verify the parameter related to the "Accessibility and suitability" area, "Habitable" category, and performance indicator "Minimum internal height 2.7 m" is reported to comply with the minimum requirements prescribed by regulations (Figure 3).

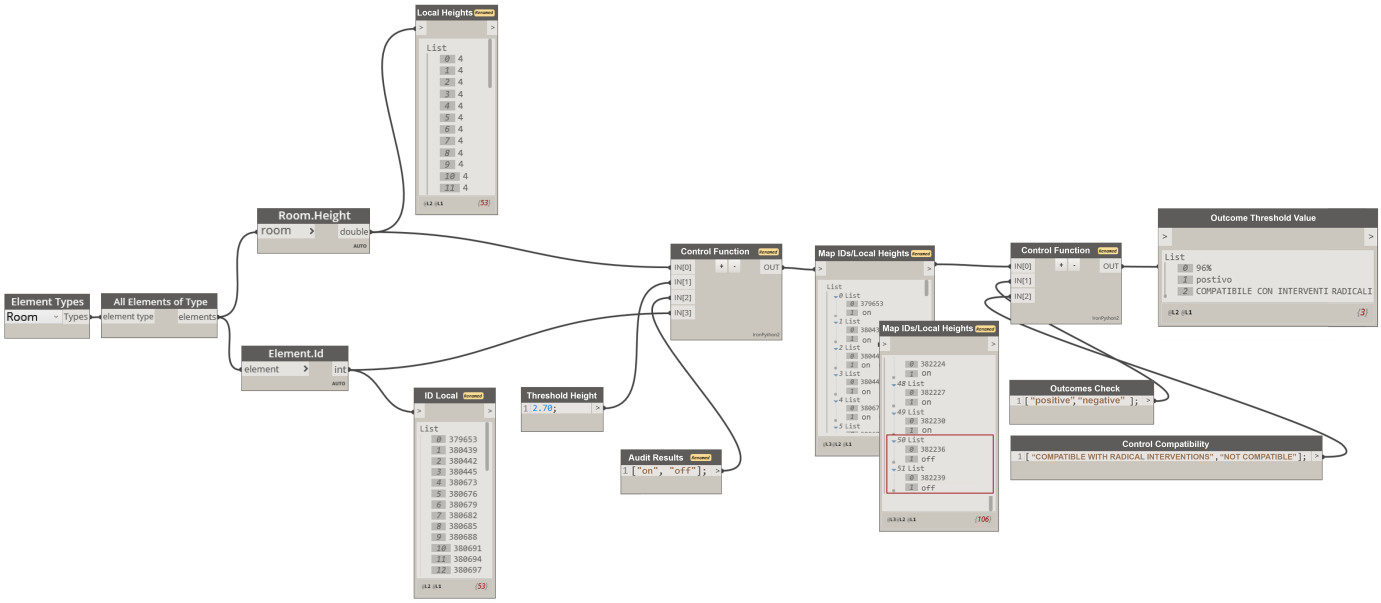

Figure 3. Example of the algorithm for verifying the height of internal spaces.

Dynamo enables the insertion of Python script nodes to allow users to automate complex operations, customize workflows, and integrate with other software [54]. Moreover, Python is a widely used and advanced programming language that enables access to external libraries and complex data management [55,56].

The first nodes of Dynamo gather a list of all the environments present in the project, extracting the data under examination for each environment, i.e., the height. The second part of the code was developed using the Python node (Figure 4), which allowed the definition of an input and output control function to query the model through the criteria and evaluation elements to which a reference value of 2.7 m was assigned.

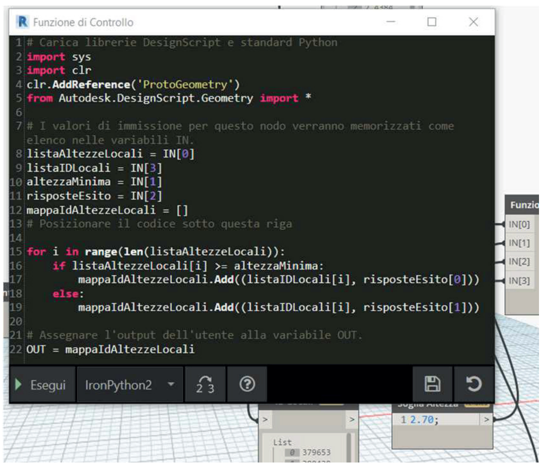

Figure 4. Python script node for control function using the logic described by "IF-ELSE" type rules.

The programming language format example enables such checks to be performed and evaluates the performance indicator:

- Internal heights lower than 2.7 m are identified as not verified (Off);
- Internal heights equal to or greater than 2.7 m are verified (On).

The results of the model heights are thus returned by the node called "ID/Local Heights Map." This procedure, applied to each category, allows for an evaluation of each internal environment of the building.

After verifying the internal heights, the third part of the code, also developed with the Python node (Figure 5), allows for calculating the total percentage of verified rooms.

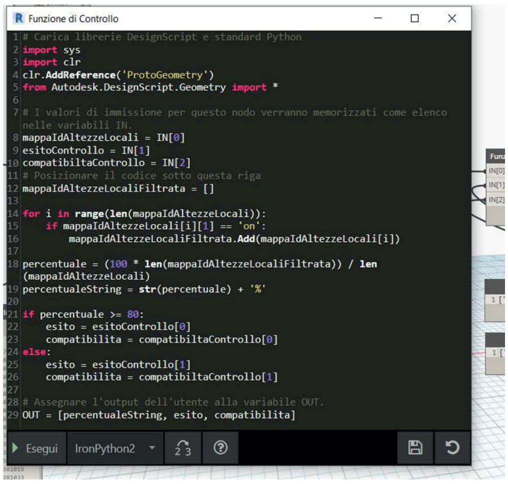

Figure 5. Python script node for compatibility control function using "FOR Loop" and "IF-ELSE" logic.

The overall result visualization for verifying adaptive reuse intervention compatibility is performed in the last node, "Threshold Value Outcome." In this example, the overall result of the internal heights of the building is positive because it is higher than 80%; therefore, according to the evaluative parameter table, it is "compatible with radical interventions."

In this context, Dynamo has proven to be a useful tool for developing algorithms capable of extracting information from BIM models and performing automatic analyses. However, Dynamo is a specific tool for processing BIM data and is only sometimes the ideal solution for processing geospatial data [57].

The verification of performance indicators in the "Site Quality" area can be carried out through GIS technology, in which geographic data can be extracted through layers, a logical collection of data used for map creation (Figure 6).

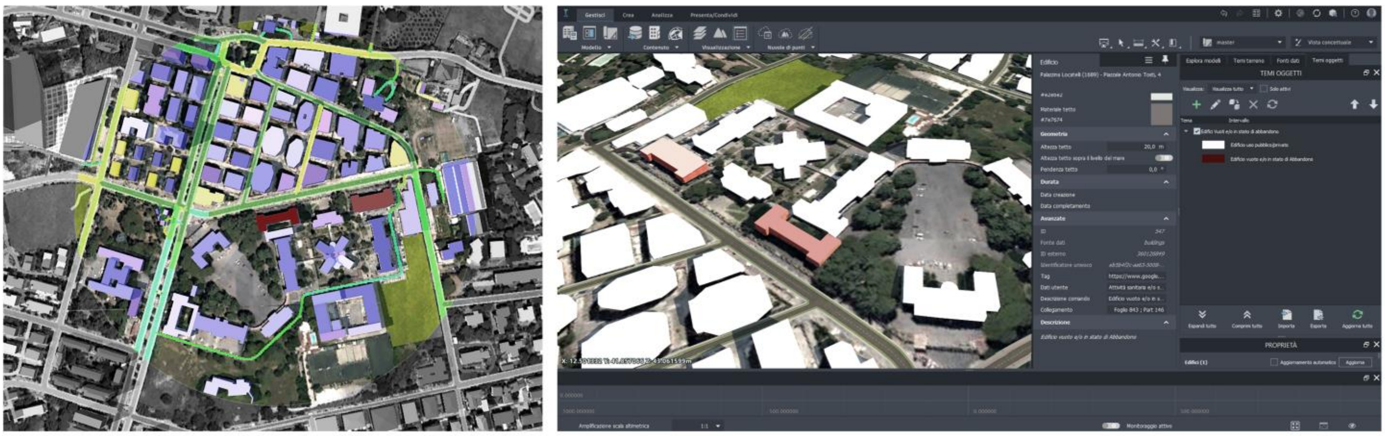

Figure 6. Services within a radius of 500 m from the property under study and case study recognized in Infraworks as "Empty and/or Abandoned Building."

In such cases, GIS software that supports Python can perform geospatial analysis on geographic data [58]. Among the most widely used GIS software that supports the use of Python are ArcGIS, QGIS, and GRASS GIS.

InfraWorks was used as the software tool to integrate Esri services through ArcGIS Online in this case study. This integration enabled access to Esri maps, data, and analysis services directly within the InfraWorks environment, providing a seamless workflow for incorporating geospatial information into the model.

Using Dynamo in InfraWorks has provided the opportunity to automate some activities, such as calculating the distance between a building and existing services, enabling geospatial analysis, and urban planning. To extract GIS data from InfraWorks, the Autodesk InfraWorksAPI Python library [59] can be used, providing a set of functions and classes to access InfraWorks data and perform operations such as data extraction, geometry modification, or property updates (Figure 7).

```python
# importa la libreria InfraworksAPI
import InfraworksAPI as iw

# crea una connessione al modello di Infraworks
model = iw.InfraworksModel('C:\\path\\to\\model.iw')

# recupera la lista dei layer di tipo GIS dal modello
gis_layers = model.ListGISLayers()

# per ogni layer GIS, estrai i dati e salvali in un file
for layer in gis_layers:
    # recupera i dati del layer
    gis_data = model.GetGISData(layer)

    # salva i dati in un file CSV
    with open(f'{layer.Name}.csv', 'w') as f:
        f.write(','.join(gis_data.Headers) + '\n')
        for row in gis_data.Rows:
            f.write(','.join(row) + '\n')
```

Figure 7. An example of automatically extracting GIS data from InfraWorks using Python and the Autodesk InfraWorksAPI library.

The script uses the 'InfraworksModel' function to connect to the InfraWorks model, the 'ListGISLayers' function to retrieve the list of GIS layers in the model, and the 'GetGISData' function to extract the data from each layer and save it in a CSV file.

The acquired data can be imported into Revit and viewed in dedicated tables, and then subjected to automatic analysis through custom nodes in Dynamo, allowing for greater flexibility in manipulating and processing geospatial data within the Revit modeling environment.

Finally, a Python script was developed in Revit to create a custom node in Dynamo that automates the distance check between geospatial services, producing a positive or negative result based on the proximity analysis (Figure 8).

This script defines three input ports: services, bank, and post office, which, respectively, represent a list of geospatial services, the coordinates of the bank, and the coordinates of the post office. The 'distance' function calculates the distance between the points. Subsequently, the script calculates the distance between the services, the bank, and the post office and stores the result in a 'result list', which is returned as output. The output will be "Positive" if the distance is less than 2 km and "Negative" otherwise.

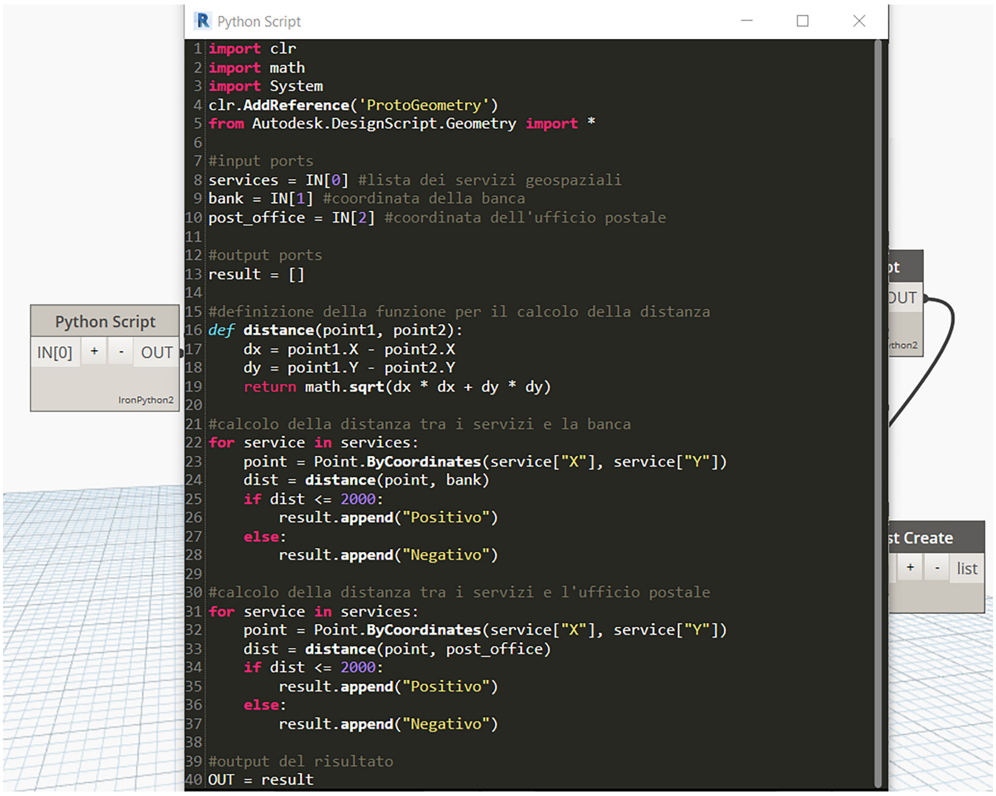

Figure 8. Shows the Python script node for the distance check function of geospatial services.

4. Results and Discussion

Thanks to the integration of Revit Autodesk, Dynamo, and Power BI, extracting the checks of the "threshold values" applied to the building in question was possible, representing an important step forward in the evaluation process. Combining these tools has simplified and improved data analysis, allowing for a more accurate and detailed building assessment. This integration has provided a complete perspective of the building, providing information on its architecture, energy performance, compliance with current regulations, and potential for adaptive reuse in terms of building residences.

Figure 9 shows an example of a dashboard generated with Power BI that allows you to visualize the audit results carried out with the proposed tool and easily compare different buildings to plan adaptive reuse interventions more efficiently.

Adopting a data-driven approach has become important in all market sectors, including real estate. The complexity of managing existing building stock undoubtedly requires adopting all approaches and tools to support such activity. The importance of reuse and the need to develop tools to promote and facilitate a reuse intervention is related mainly to the composition of the Italian building stock and housing demand. The reuse of existing stock for residential purposes is a real opportunity not only to achieve objectives of less land use, less resource use, and energy efficiency for greater environmental sustainability but also to respond to the demand and housing needs of a population that increasingly requires smaller-sized housing, in which radical restructuring is not necessary.

The proposed tool allows for quick evaluations and comparisons of nonresidential buildings to support decision-makers using the latest digital technologies. These technologies can also support geolocation, cataloging, and classification of buildings in a state of abandonment and decay based on their potential for conversion to residential use. They, therefore, provide support for planning adaptive reuse interventions, promoting the gradual transition of the construction sector toward a circular economy system.

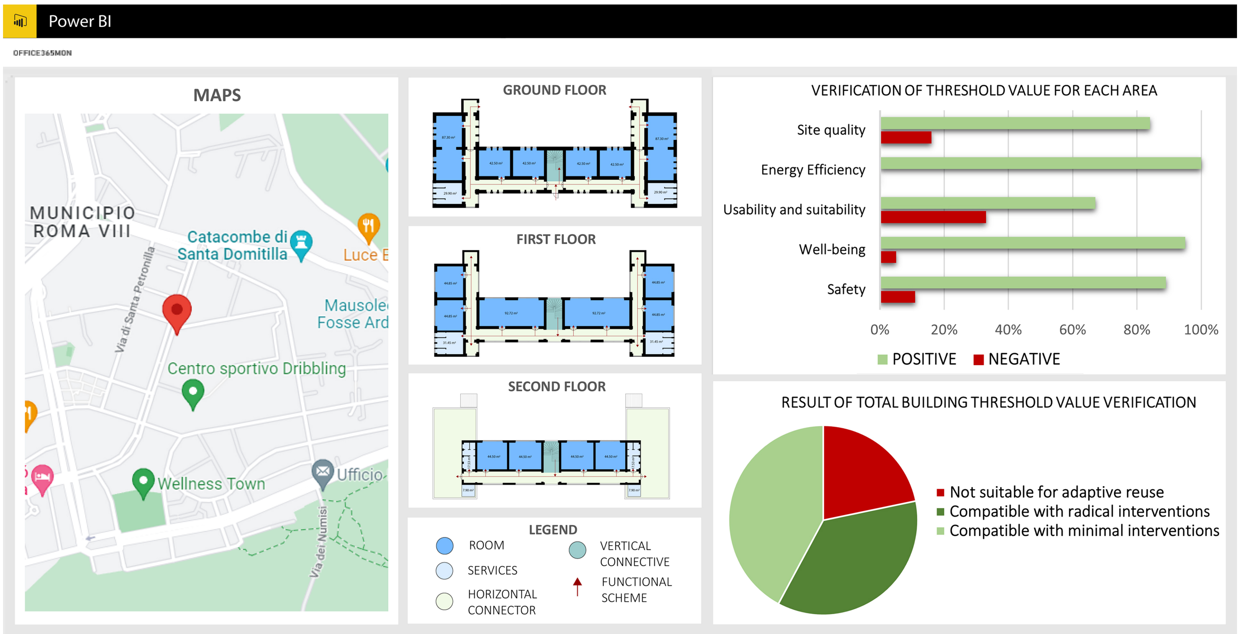

Figure 9. Dynamo evaluations output rendered in Power BI in a BIM environment.

5. Conclusions and Future Development

Recent decades' social and economic changes have reshaped the residential real estate market, both in terms of supply and demand. These changes have increased housing distress and deprivation, a predominantly urban phenomenon, particularly in larger cities. In this context, buildings' adaptive reuse and energy efficiency are fundamental in reducing living costs and improving residents' quality of life [60,61].

This situation requires verifying the opportunities and potential offered by the adaptive reuse of existing building stock and developing solutions to create quality residential buildings.

This way, promoting and accelerating the transition to a circular economy is possible, which constitutes an additional challenge for cities, institutions, and individuals. Numerous virtual initiatives adopted internationally will have to become actual integrated and systemic circular models. According to some studies, the adaptive reuse of existing buildings can significantly improve the built environment's energy performance, reducing greenhouse gas emissions and energy consumption [62].

The emergency period has highlighted the importance of adopting solutions for the adaptive reuse of spaces and technology to optimize the complex management of the built environment.

In relation to this, this contribution proposes an analysis method based on current trends in the adaptive reuse of existing building heritage, which constitutes a starting point with solid scientific foundations for initiating a discussion among all stakeholders involved in this issue.

The main limitation of applying the research outcomes on a large scale to real estate is related mainly to the still limited diffusion of digital technology in the construction sector.

As a future development, a BIM and GIS tool could be created to automatically identify the improvement interventions for the specific case study to be energy-efficient according to the environmental conditions such as wind, solar radiation, temperatures, precipitation, and relative humidity. The tool can also be integrated with the parameters provided by municipal building regulations governing construction methods to identify possible adaptive reuse interventions.

The implementation of artificial intelligence (AI) algorithms may improve the ability of the BIM/GIS model to analyze data and suggest more efficient and environmentally sustainable adaptive reuse solutions. In addition to the integration of BIM and GIS technologies, the use of advanced sensors and Internet of Things (IoT) devices could further enhance the data collection and analysis process, providing real-time information on building performance and environmental conditions. Furthermore, the implementation of machine learning algorithms could improve the accuracy of predictions and identify potential issues before they occur.

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