sustainability

MDPI

Article

Assessing the Transformability of Public Housing through BIM

Giovanna Acampa [1], Lorenzo Diana [2,*], Giorgia Marino [1] and Rossella Marmo [3]

1 Faculty of Engineering and Architecture, University of Enna Kore, Cittadella Universitaria, 94100 Enna, Italy; giovanna.acampa@unikore.it (G.A.); giorgia.marino001@unikorestudent.it (G.M.)
2 Department of Civil, Building and Environmental Engineering, University of Naples Federico II, 80125 Naples, Italy
3 Department of Civil Engineering, University of Salerno, 84084 Fisciano, Italy; rmarmo@unisa.it
* Correspondence: lorenzo.diana@unina.it; Tel.: +39-081-7682144

Abstract: Public residential buildings make a large portion of the European existing stock and they quite often require deep renovation interventions. A methodology for setting priorities and targeting regeneration investments should be defined relying on the increasing use of building information modelling (BIM) tools even for managing existing buildings. The aim of this paper is to integrate the evaluation process into BIM Revit software developing a specific plug-in, a Decision support system (DSS) that will help to identify the most appropriate flats to be transformed. It is based on measuring three indicators: Usability, Fragmentation, and Constructive Modifiability. Through their weighted average it is possible to obtain a final transformability score. The proposed approach has been tested on a case study chosen within the 1st P.E.E.P. (1st public plan for council and affordable housing) that has been approved in Rome in 1964. The results demonstrate that the transformability of apartments is related mainly to the Constructive Modifiability indicator and buildings with reinforced concrete frames show higher scores. A widespread application of such a methodology on large real estate portfolio may lead stakeholders involved in housing management investments in clear choices related to maintenance of buildings.

Keywords: existing buildings; public housing; transformability; BIM; Revit; DSS; performance assessment

check for updates

Citation: Acampa, G.; Diana, L.; Marino, G.; Marmo, R. Assessing the Transformability of Public Housing through BIM. *Sustainability* **2021**, *13*, 5431. https://doi.org/10.3390/su13105431

Academic Editor: Jorge de Brito

Received: 10 April 2021
Accepted: 8 May 2021
Published: 12 May 2021

1. Introduction

Existing buildings or districts can be an important resource not only as a tangible symbol of a community but also because their renovation is crucial for a smart growth approach. Repurposing old buildings—particularly those that are vacant or in very bad condition—reduces the consumption of land, energy, materials, and financial resources. Given these assumptions and taking into consideration the increasing use of BIM (Building Information Modelling), even to manage existing buildings, it is necessary to integrate the existing BIM tools with an appropriate evaluation system aiming to support decision-makers in maintenance actions complying with budgets.

Residential buildings in Italy account for 40% of energy consumption and 36% of emissions [1,2] of the existing building stock. Respecting indications from European Directives (2010/31/EU) and world agreements on climate [3], it appears essential to decrease energy consumption in residential buildings by proposing deep renovation interventions especially in countries with an ancient building stock. In Italy, around 60% of buildings have been built before the 1970s [4], before the first law on the control of energy consumption for thermal use in buildings was approved (Law n. 373/1976). Buildings' obsolescence relates also to their structural behavior, since the first law for construction in seismic zones passed in 1974 (Law n. 64/1974), and to apartment layouts, since buildings were built in a historical period with different social needs. According to Istat (Italian Institute for Statistics), the number of family members dropped from 3.4 in 1971 to 2.3 in 2019 [5].

A large portion of the Italian built environment, thus, needs to be renovated to address novel social, economic, structural, and environmental needs.

Particularly, 9–15% of urban population lives in Public Residential Buildings (Edilizia Residenziale Pubblica, ERP) [6], which constitutes a significant percentage of housing stock in European cities. Especially in Italy, ERP stock accounts for 836k apartments, for a total amount of 2.2 million inhabitants (3.7% of families) [7]. A huge share of ERP apartments are located in post-WWII buildings, the so-called "great-size" interventions, started in the 1960s and characterized by prefabrication, industrialization and located in suburbs outside the historic centers [8]. Due to the widespread current state of obsolescence and inadequacy, most of the post-WWII ERP buildings require retrofit interventions [9]. Several efforts have been done in the last few years concerning the seismic-energy retrofitting strategy for residential buildings [10–16]. Nevertheless, regeneration processes have a substantial impact on all the three pillars of sustainability (social, economic, and environmental) [17] and, concerning ERP stock housing, it should respect a holistic approach addressing not only energy interventions and structural strengthening but also new living spaces and new apartment architectural reconfigurations which better respond to user needs [18,19]. The goal of ERP housing renovation is to define regeneration interventions that integrate functional and spatial aspects with technological and constructive ones, combining retrofit with the demands of contemporary modification projects of suburbs [20].

In addition to energy and structural issues, the main problems in post-WWII ERP housing stock are related to the architectural configuration of apartments, such as: (i) dimension—apartments reveal to be too big if related to the current needs; (ii) apartment layout—strong separation between sleeping and living area; (iii) dimension of living area—small living areas; (iv) natural lighting—low amount of natural daylight. For such reasons, holistic strategies are needed: interventions should address energy consumption reduction (such as the addition of thermal insulation on envelope elements, the substitution of windows, the substitutions of heat generators), structural strengthening (addition of bracing elements, restoration of concrete elements) and typological reconfigurations of apartments. A well-appreciated strategy concerning architectural and typological reconfiguration is the splitting of big apartments. In the case of small living areas, the addition of an external exoskeleton [10,13–15], following the typological solution of Lacaton and Vassal on public housing [21], can help brace the load-bearing structure, adding insulation and new greenhouses on the existing envelope and incorporating the related surface into living areas of apartments. Furthermore, intervening on the internal layout may help the realization of apartments with fewer partitions to determine wider flexibility of use.

In the last few decades, several case studies among Europe have shown evidence of ERP retrofit strategies. Especially in the Netherlands, a huge share of ERP stock underwent renovation and transformation works [22]: Bijlmermeer [23–25], Osdorperhof [25,26], De Leeuw van Vlandereen [27] (Amsterdam) and Lage Land [25] (Rotterdam) are an example of best practices of sustainable regenerations which led to energy consumption reduction, social, environmental, and economic benefits [28].

The current work delineates an approach to support stakeholders in decision making concerning their public real estate management. Decision support systems (DSSs) [29] are needed to identify the most appropriate apartments or buildings within large portfolios on which retrofitting interventions should be addressed. The paper aims to develop a specific plug-in to integrate automatic evaluations of single apartment transformability into the BIM environment. The regeneration of buildings is supported by a list of indicators able to delineate the propensity of apartments to be transformed so to meet current requirements and user's needs. The above-mentioned procedure is applied to specific ERP case studies of the city of Rome, realized during the 1970s and the 1980s and today showing important critical issues that must be considered for retrofit intervention.

1.1. State of the Art

The complexity related to management and regeneration strategies of existing buildings might be coordinated by BIM. In the first place, it allows collaboration and information exchange among the actors involved during the life cycle of an asset (e.g., designers, owner, employee, facility manager, and users); secondly, it can store and process data related to elements properties (e.g., quantities, materials properties and user-defined properties); finally, it provides for a powerful user interface enabling further spatial analysis (e.g., space management). Furthermore, a building information model is by default the digital inventory of a certain asset, so that not only the quantity take-off is automatized, but also the inventory management is facilitated. Even if BIM for existing buildings is increasingly widespread in the last years, its complexity and costs hinder its use by single owners. Otherwise, it could be extremely useful for Public Administrations to manage their huge number of apartments for social housing.

In the progressive dissemination of BIM methodology, an important role is carried out by legislation, both European and national, whose evolution resulted in a strong increase in Building Information Modelling adoption.

The starting point in Europe is the European Union Public Procurement Directive 2014/24 of 26 February 2014, which called EU Member States to "encourage, specify or impose" by 2016 the use of BIM as a reference standard for all projects financed with public resources. In 2016, the EU BIM Task Group was established with an aim "to deliver a common European network aimed at aligning the use of Building Information Modelling in public works". The establishment of the group has brought to a wider BIM adoption throughout Europe (Figure 1).

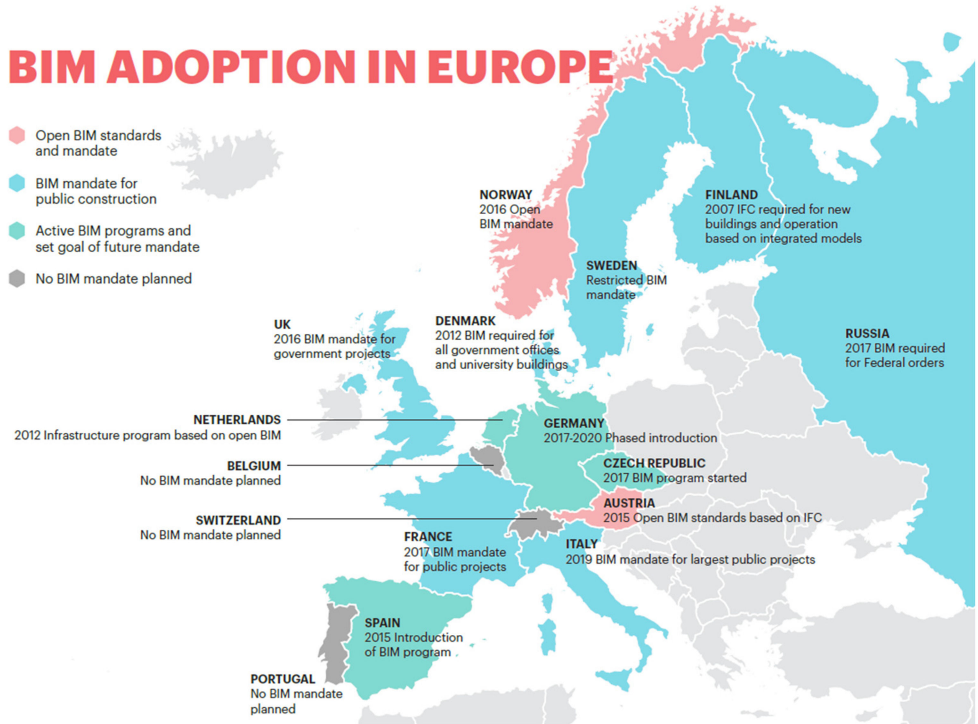

Figure 1. BIM adoption in Europe updated to 2020. Source: McAuley, B., Hore, A. and West, R. (2017) BICP Global BIM Study—Lessons for Ireland's BIM Programme Published by Construction IT Alliance (CitA) Limited, 2017.

In Italy, the main law transposing EU directives on public procurement was Legislative Decree n.50 of 18 April 2016 [30] called new Public Contracts Code, that introduced BIM and started a regulatory process.

BIM has been also integrated into the debate on new methodologies and technologies through the UNI 11337:2017 publication.

Such a trend in the adoption of BIM is mainly related to new constructions, especially for performance evaluations, while the use of BIM as a decision support tool in the management and redevelopment of existing buildings is desirable shortly. BIM holds undeveloped possibilities for providing and supporting Facility Management practices with its functionalities of visualization, analysis, control, and so on [31]. At the same time, there is a lack of studies focused on the transformability of housing stocks [32]. Due to the compelling needs of shaping a more sustainable built environment, especially provided by the refurbishment of existing buildings, it is of great interest the development of BIM applications for these purposes. These are the main reasons behind this paper. The next sections provide a review of BIM uses for performance assessment and current assessment tools for existing buildings, which are the essential background of the novel approach proposed by this paper.

1.1.1. BIM and Performance Assessment

According to EN ISO 41011:2018, performance can be defined as a "measurable result". Performances can be related to activities, processes, products, systems and organizations and they concern either quantitative or qualitative findings. Building Performance Assessment (BPA) is essential to understand in which measure a building has met established requirements. A correct comprehension of the building behavior and criticalities allows to make correct decisions at the right time. Building Information Modelling can play a key role when it comes to inspect and analyze a building, as it offers an integrated and consistent database. Building information models may contain information to perform specific analyses (e.g., structural, lighting, energy, etc.) carried out in the very same platform (e.g., Autodesk) or employing interoperable tools. BIM applications and software have produced a deep change in the AEC (Architectural Engineering and Construction) sector. They provided a great level of control over design, automated drawing extraction, automated material take-offs, parametric behavior of building components and better coordination and interoperability between different actors. Depending on the project requirements several tools might be needed, requiring data to be transferred or even reworked. Thus, it is of great value the development of user-customizable plug-ins within BIM software. Their introduction brings the assessment capabilities right into the design environment (avoiding data migration), also implementing mechanisms able to meet requirements set by designers and stakeholders. A commonly used BIM software is Revit, whose capabilities can also be extended by several plug-in related to architectural, structural, mechanical, plumbing, electrical design, energy simulation, rendering and others. In general, Revit extension tools are meant to improve both interoperability and information management, such as importing and exporting data and files [33]. BIM software includes computer-aided design (CAD software) products used commonly within the architecture and construction industries. Many of these products offer tools and libraries specifically targeted toward architectural design and construction, including mechanical, electrical, and plumbing (MEP). For the purposes of BPA, building information models are of great value as they can be enriched with actual performance information.

A Performance Information Model has been proposed as a model meant to support facility management by gathering and analyzing relevant information related to residual performances and operational conditions of an asset and its elements [34]. Such a model can support the evaluation of the need of intervention in different application areas. As an example, in the housing field several indicators can be defined, moving from architectural, energy and structural issues to transformability evaluations [32]. Similarly, providing adequate housing quality to older people is another relevant topic that can be addressed by using a set of indicators to assess the age friendliness of housing [35].

BIM-based workflows have been proposed to integrate Key Performance Indicators with BIM tools for maintenance management and performance assessment [34,36–38]. Recently, the evaluation of the building performance indicator, developed by Shohet et al. [39] has been transposed in BIM environment [40], using Dynamo and Revit. This process allows calculating the systems' and the whole building's performances in an automated way. To track the real-time building's performances, building sensors technology and BIM have been integrated by a user-friendly Navisworks add-in program [41]. Nevertheless, research on BIM for the operational phase management is still in its early stage and most of the current research has focused on energy management [42]. In this regard, BIM has been applied to overcome building energy performance gap [43], for simulating building performances and optimizing energy efficiency of residential buildings [44], confirming energy and money saving [45]. It has been emphasized that energy simulation and optimization processes that are BIM-based can improve the construction process as well as enabling alternative design solutions [46] and that integrating BIM and architectural design is recommended for achieving high quality living spaces and energy conservation [47].

Due to the increasing interest in providing a more sustainable built environment, efforts in including building sustainability assessment into BIM environments have been emerging in the last years too [48–50]. In particular, Jalaei and Jrade [50] have proposed a customized plug-in for Revit to facilitate the assessment of LEED indicators within a BIM environment. Additionally, BIM offers opportunities to manage the intrinsic complexity of a building supporting the development of seismic risk assessment procedures [51–53].

Evaluation logics have been integrated with BIM to improve space design and user satisfaction [54] and to analyze the indoor circulation [55].

In the context of decision support systems, Revit has been used for the generation of optimal renovation scenarios [56] that are based on five criteria: energy consumption, investment cost, thermal indoor comfort, aesthetic and spatial quality. A Revit plug-in, named value creation by building renovation, has been developed to guide the user through the evaluation process, enabling the comparison of the resulting scenarios too. The exposed results have the potential to aid architects together with other stakeholders to develop holistic renovation scenarios and to make informed decisions in a shorter period.

To sum up, BIM has so far been applied to the performance assessment process for both new construction, operational activities, and renovation proposals. At the operational phase, which is of primary interest for the scope of this paper, BIM processes ensure qualitative and quantitative data and information that can support decision making procedures, especially when models are integrated with evaluation tools and actual/residual building performances.

1.1.2. Assessment Tools for Existing Buildings

DSSs are fundamental tools in urban regeneration processes especially in the phase of evaluation of existing qualities and definition of retrofitting strategies. Only after built environment evaluation, it is possible to indicate any further modifications. No successful regeneration process can be activated if not supported by a valid DSS.

Concerning the existing quality assessment phase, over the years, scientific research has developed various tools capable of supporting decision-makers. In the framework of the international research CostTU0701—Improving the Quality of Suburban Building Stock [57] several systems for quality assessment of peripheral residential complexes have been studied and classified. Quality assessment tools allow us to simultaneously analyze different aspects at different scales. Concerning suburban residential complexes, the concept of quality is referred to three main aspects [58]: (i) housing quality—referred to performances of internal and external spaces; (ii) Environmental quality—referred to indoor and outdoor comfort conditions; (iii) Technological quality—referred to performances of the technological system.

Depending on the quality to be assessed, indicators provide a numerical quantification of specific requirements. This numerical quantification guarantees comparability and measurability, a prerequisite for comparing different aspects in multi-criteria methods. To compare different qualities, evaluations at different scales are needed, ranging from the level of the apartment (and even to individual rooms) to the level of the whole building (and even to neighborhood scale).

DSSs were introduced in the 1970s without aiming to replace human judgment but rather to support decision makers, who still have control of the process [59], throughout the planning process. Within DSSs, particularly appreciated are multi-criteria methods which, through the composition of different indicators, express an overall judgment about qualities and quantities evaluated [58]. Regarding multi-criteria methods for design quality assessment, in recent years there has been a worldwide spread of methods [60]. Multi-criteria methods can be classified based on the scale of application: regional and urban scale, urban fabric scale, building scale, housing space scale, technological system scale. Concerning performance assessment of buildings, Building Performance Evaluation (BPE) methods are distinguished in different assessments depending on the phase of the life cycle of the building analyzed. Preiser in 2005 [61] clarifies that the BPE Process Model is a loop of different evaluation phases and processes. The different phases are: planning (phase 1); programming (phase 2); the design (phase 3); construction (phase 4); employment (phase 5); reuse or recycling (phase 6). Each phase corresponds to a specific evaluation process. This paper addresses phase 6 "reuse and recycling". In recent years, several tools appeared on the market, both multi-criteria methods and design validation protocols and design support software simulating building behavior (energetic, structural, microclimatic, etc.), that support designers and decision-makers in operating re-design strategies. These assessment tools prove to be an important support for verifying even design choices and maintenance strategies [62].

With regard to the verification and control of the design choices with a view to regeneration, at first, the EU funded the JOULE research program which led to the genesis of a new generation of specific support software tools for retrofit interventions, TOBUS and EPIQR [63]. The goal was to develop tools aimed at evaluating retrofitting strategies, costs, and activities aimed at meeting the needs of both reducing energy consumption and improving internal environmental quality [64]. Concerning the evaluation of design qualities, important research appeared in the Netherlands [65] and in Italy, for example the SIVA-SISCo quality method [66,67]. Of particular interest, among the evaluation methods based on user questionnaires, is the DQI [68]. Although based on qualitative judgments, the method is particularly interesting because it identifies criteria for building quality assessment. The structure of the DQI method starts from the Vitruvian tripartition assumption in *utilitas*, *firmitas* and *vetustas* [69].

In recent year, DDSs are more specifically renovation oriented: RE.SIS.TO Project defines a simplified procedure for seismic vulnerability estimation and retrofitting intervention strategies [70]; Kamari et al. [71] define a system to combine several scenarios for energy retrofitting interventions, even involving BIM modelling [56]; Danilovic and Browing [72] defines a complex domain mapping matrix to choose among hundreds of possible scenarios the most convenient in terms of general sustainability; Artino et al. [73] propose a simplified DDS for the definition of strategies for both seismic and energy retrofitting of reinforced concrete frame buildings.

Historically, support indicators have always been used to guide designers in the choice of appropriate layout solutions. In this way, important achievements have been reached by the modern movement: at the end of the first World War, rationalism deeply focused on minimal requirements for low-cost housing [74,75]. The introduction of concepts such as the *existenzminimum* was the driving force for the definition of affordable housing projects, according to the logic of maximum results with the minimum economic effort [76]. Gropius, Le Corbusier and not least Klein introduced—in housing design—dimensional solutions supported by suitable indicators that guaranteed the satisfaction of minimum needs and hygiene standards [77]. Klein's studies tended to define an objective approach for evaluating functional and economic problems of housing by the definition of a relevant method for apartment plan evaluation integrating evaluation questionnaires, comparative analysis, and graphic interpretations, based on some objective indicators: *betteffeckt* (covered area divided by number of beds), *nutzefekt* (net area divided by covered area), *wohneffekt* (living area plus bedroom area divided by covered area) [78].

2. Materials and Methods

2.1. Transformability in Housing

To support decision-makers in managing their real estate, DSSs should investigate the propensity of buildings to be transformed due to their inner capacity to support renovation interventions. A more transformable building reduces renovation costs. In this way, concepts such as transformability should be introduced in evaluation methods for real estate management and retrofitting strategy determination. Transformable buildings can be easily altered and foster the reuse and recycling of entire constructions, single components and their materials [79]. Transformability stands for the possibility of housing buildings to be transformed undergoing renovation interventions that allow different layouts compared to the existing one, guaranteeing an adequate response to new requirements and user needs. The transformability of a building is defined as "its intrinsic tendency to modify itself to make possible new modes of use; however, this tendency must be realized in a way that is suitable with [...] the typological layout of the pre-existence" [80]. The concept of transformability escapes the goals of the most common evaluation tools. In the logic of regeneration of contemporary cities and buildings, in particular suburbs, the ability to evaluate the predisposition of buildings to undergo interventions becomes a key topic, allowing to understand the effective drivers of transformation.

Constructive features and architectural layout have a strong influence on the potential transformation [81]. To quantitatively compute this potential, architectural and functional housing features should be investigated. Typological indicators can be introduced and organized according to a space subdivision of the building. According to the UNI Norm 10838:1999 ("Edilizia—Terminologia riferita all'utenza, alle prestazioni, al processo edilizio e alla qualità edilizia."), spaces in buildings are organized into nested cluster levels, starting from the level of the building itself up to apartments and zones. In Figure 2 the hierarchical subdivision of buildings is shown. The clustered levels are: the Residential Organism (OR), corresponding to the building itself; the Aggregate Module (MA), that for bars corresponds to the different staircases; the Elementary Typological Module (MTE), corresponding to the organization of the different stories; the Apartment (APA). Levels arrive up to zones of apartment and rooms. In the framework of the present work, the transformability is investigated using indicators concerning exclusively apartment level.

2.1.1. The Use of Transformability Indicators at Apartment Level

Concerning the investigation of apartment transformability, three specific indicators have been introduced: Usability, Fragmentation, and Constructive Modifiability.

- The Usability indicator expresses the quantitative relationship between service spaces (i.e., meant for distribution, bathrooms, toilets, deposits, hallways, etc.) and served spaces (rooms and kitchen) [78,82]. Numerically this is expressed by the ratio between total rooms served area (excluding bathrooms and corridors) and net area (service rooms + served rooms) (1). The surfaces calculation will be net of internal partitions and the structure and balconies outside the flats. The higher the incidence of served space is, the more the surface is exploited and therefore the possibilities of transformation without expensive changes will be reduced. The lower the usability is, the more the transformation has margins because distributions and bathrooms are oversized.

$$U = \frac{total\ served\ areas}{net\ area}\,[\%] \tag{1}$$

- The Fragmentation indicator provides information concerning the apartment layout by relating the amount of external and internal borders to the total area available [82]. Numerically this is expressed by the product of external wall length and internal wall length divided by the gross area (2). The Fragmentation indicator provides the incidence per square meter of internal and external walls and therefore the entity of transformation costs. The higher the fragmentation value is, the higher the cost of the demolition and reconstruction will be.

$$F = \frac{WL_{ext} \times WL_{int}}{gross\ area}[-] \quad (2)$$

- The Constructive Modifiability indicator: which relates the changeable parts of the apartment to invariant elements [78,82]. Numerically, it is expressed as the ratio between Non-Modifiable Element total area (in plan—identified in structural and plant elements) and gross area (3). The Constructive Modifiability indicator strongly affects the possibility of modification. It is strictly related to the constructive features of the building and the technological systems installed.

$$CM = \frac{A_{tot,NME}}{gross\ area}[\%] \quad (3)$$

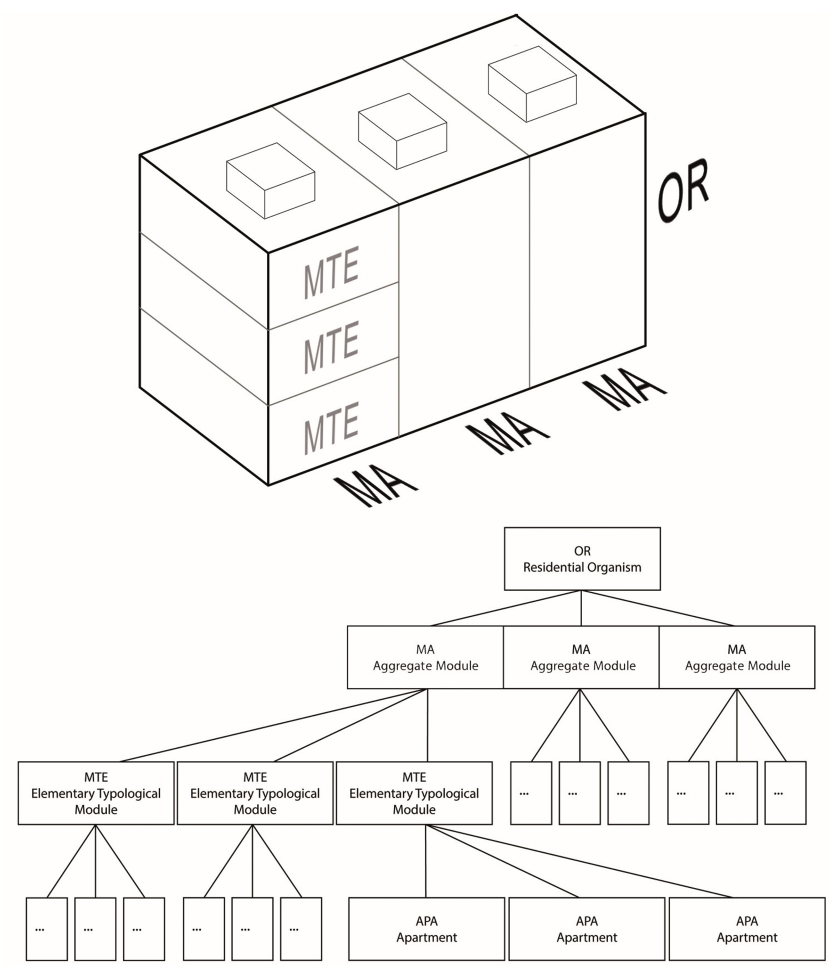

Figure 2. The hierarchical subdivision of residential buildings.

2.1.2. Normalization and Weighting of Indicators

To determine the transformability score of a building and specifically of an apartment, indicators should be compared thanks to a normalization process, leading to a final numerical value. Scores from one to five are assigned to the above-mentioned indicators, identifying the level of transformability related to each aspect investigated.

The normalization process is carried out in the following way:

- Usability: the usability percentage value is normalized according to a decreasing appreciation curve with concavity pointing downwards [66,67]. The value 90% has been established as the lower boundary and the value 50% as the higher value assuming that an apartment with a lower usability has a huge presence of connective spaces in plan meaning a higher freedom to reorganize the space in case of renovation intervention. In Table 1 single boundaries are shown.

Table 1. Usability normalization.

Usability Score Normalization	
$5 \leq$ Score < 4	50.0% $\leq$ U < 72.0%
$4 \leq$ Score < 3	72.0% $\leq$ U < 80.8%
$3 \leq$ Score < 2	80.8% $\leq$ U < 86.4%
$2 \leq$ Score < 1	86.4% $\leq$ U < 90.0%

- Fragmentation: the normalization is done through a decreasing curve with concavity downwards, indicating the reduction of transformability as the internal fragmentation increases. An apartment with a higher incidence of internal and external walls needs higher costs related to demolitions. Boundary values have been established by considering famous and symbolic housing projects. The lower boundary value is 0.00, represented for example by Maison domino, an open-plan structure designed by Le Corbusier for serial production. In the case of "essential apartments", realized by Franco Albini in Milan (via Argonne—dated 1938), walls are reduced to the minimum and the Fragmentation indicator reaches the value of 8.00. In the case of the apartments of the Unité d'habitation in Marseille (Le Corbusier) the fragmentation indicator arises up to 12.50 showing how the layout of a non-fragmentated apartment that is long and narrow implies a higher incidence of internal and external walls. In Table 2 boundaries between the scores are shown.

Table 2. Fragmentation normalization.

Fragmentation Score Normalization	
$5 \leq$ Score < 4	0.00 $\leq$ F < 11.00
$4 \leq$ Score < 3	11.00 $\leq$ F < 15.40
$3 \leq$ Score < 2	15.40 $\leq$ F < 18.20
$2 \leq$ Score < 1	18.20 $\leq$ F < 20.00

- Constructive Modifiability: the normalization is completed through a decreasing curve with concavity upwards, showing the reduction of transformability as the incidence of non-modifiable elements increases. Such an indicator is strongly affected by constructive features of the building: reinforced concrete (r.c.) frame structures have a lower incidence of non-modifiable elements and therefore a higher freedom of intervention in the definition of renovated apartment layout. Otherwise, in buildings realized with load-bearing r.c. walls the freedom in organizing renovated layout is limited by the presence of walls itself. In Table 3 boundaries between the scores are shown.

Table 3. Constructive Modifiability normalization.

Constructive Modifiability Normalization	
$5 \leq$ Score < 4	1.00% $\leq$ CM < 2.21%
$4 \leq$ Score < 3	2.21% $\leq$ CM < 4.14%
$3 \leq$ Score < 2	4.14% $\leq$ CM < 7.11%
$2 \leq$ Score < 1	7.11% $\leq$ CM < 15.00%

To obtain a comprehensive transformability score, we used a simplified multi-criteria method with three indicators. For each indicator we defined: the semantic aspect linked to the meaning (description), the metric aspect linked to the measurement (indicator), and the relative aspect (weight) that expresses the criterion importance compared to the others. In our case we assume that each indicator has equivalent importance (0.333 each). In this way a final score is assigned allowing to assess by ranking different solutions in hierarchy [83].

2.2. The Introduction of Transformability Indicators in BIM

Most contemporary BIM applications support functional extension by providing what is known as application programming interface (API). Using these interfaces, expert users with knowledge in computer programming languages such as C#, C ++, or Visual BASIC can create customized functions. The developer can go as far as to create functions that might not be part of the BIM platform default configuration by integrating external evaluation or analysis tools within the BIM environment [84]. The development of different plugins could help designers to develop their tasks more efficiently and effectively. This study proposes an innovative tool for prior evaluations implementing a customized plug-in for REVIT. The proposed tool classifies the transformability of existing buildings by analyzing different indicators.

The process for defining a plug-in within BIM for evaluating building predisposition to undergo important renovation interventions includes the following steps (as shown in Figure 3): (i) definition of indicators; (ii) creation of BIM model; (iii) evaluation.

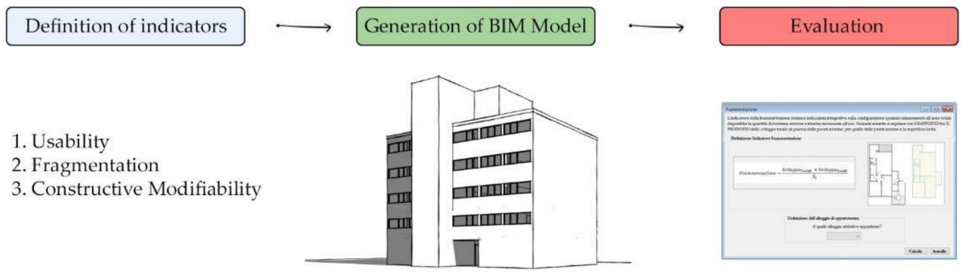

Figure 3. Main steps of the proposed framework.

1. *Definition of indicators.* The precise definition of the indicators to be investigated is a key phase to set the goals of the evaluation process for developing the plug-in. Indicators have been chosen in order to describe existing apartment characteristics: the indicators selected (in line with Section 2.1.1) have been Usability (ratio between total served area and net area, as in Formula (1)), Fragmentation (ratio between the product of the length of internal and external walls and gross area, as in Formula (2)), and Constructive Modifiability (ratio between non-modifiable element area and gross area, as in Formula (3));
2. *Creation of BIM model.* The innovation in design concept is based on simulation. The simulation is defined as the ability to manipulate a model in its definition of space and time, to allow the rapid perception of interactions which are not immediately perceptible [85]. It is no longer a tool that only helps in preparing a project, but which can transfer the entire methodological process (analysis-project-verification-management) in digital form, working on a design model that can be viewed with continuous accessibility in space and time [86,87]. The software considered for the present methodology is Revit, used here to create the building model according to design drawings. The 2D drawings are transformed into a 3D model. The model includes building geometry, spatial relationships, quantities, and properties of building components. The BIM data are classified as numeric and alphanumeric: the former represents information expressed by numbers, such as area, height, or width of the space; the latter are expressed with non-numerical values such as name, description or use of an object. Therefore, the level of detail in a BIM model increases as the

project progresses, often relying first on existing information, then developing from a simple conceptual model in a detailed virtual building model, then into an operational model. In our case, the level of definition is geometric in order to quantify data useful to evaluate transformability indicators. The Revit model must contain areas and rooms. By identifying the space category, related information, such as height, length, and area, can be extracted. Thereafter, the information's recognition leads to the calculation of an apartment transformability score. To extract objects and their properties for evaluations, rules must be defined.

3. *Evaluation.* The evaluation system is developed as a Revit 2019 plug-in. The computer programming language VB.NET combined with Visual STUDIO have been used to develop the evaluation process. First, the evaluator has to define extractable elements (areas and rooms) in the building information model to start the evaluation. For the *Usability* indicator calculation, the evaluator selects served areas included in floor plan and apartment net areas. Once these elements have been selected, the calculation is performed automatically. For the *Fragmentation* indicator calculation, the evaluator selects both external and internal wall length in plan and apartment gross areas. Once these elements have been selected, the calculation is performed automatically. For the *Constructive Modifiability* indicator calculation, the evaluator selects both non-modifiable element areas (identified in plan in structural and plant elements) and apartment gross areas. Once these elements have been selected, the calculation is performed automatically. Functions for selecting areas and rooms, and for the evaluation process (equations, normalizations, algorithms) have been coded. A user interface (UI) is developed displaying what is being evaluated and what the evaluator has to click on in the model. After data extraction and indicator calculation, to obtain a final score, results are normalized following the process illustrated in Section 2.1.2. To display the normalized score, the evaluator should click on the final evaluation button. This will open a .docx report showing the normalized results in a table. To obtain a final transformability value, the weighted average of the three values is performed.

Figure 4 shows the detailed evaluation process of the proposed BIM-based framework.

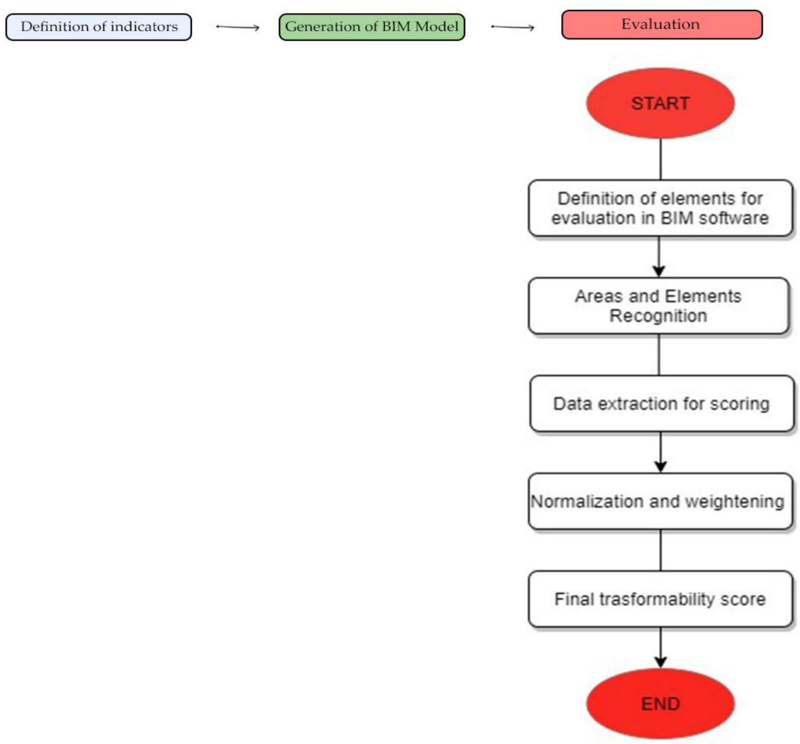

Figure 4. Evaluation process flow-chart in BIM.

3. Case Study: The 1st P.E.E.P. in Rome

To verify the reliability of the above-mentioned methodology, this has been applied to some case studies chosen within the 1st P.E.E.P. (1st public plan for council and affordable housing) that has been approved in Rome in 1964. The original program planned to settle 700,000 inhabitants. After some modifications and removals, "only" 33.7 million m^3 were realized, on a 30 km^2 area, installing 400,000 inhabitants. Despite the huge process of sales of the assets of the last few decades, nowadays the public territorial agency for council housing management of Rome (ATER) owns—within the properties of the 1st PEEP—around 50,000 apartments, for around 200,000 inhabitants.

Almost all the districts realized within the 1st P.E.E.P. share near the same design approach and constructive features: great-size bars and multi-story towers hosting residences and services realized with prefabricated envelope elements and with the application of industrialized technologies for the casting of structural elements. The design approach of great size buildings has direct consequences on the layout of apartments that in some way is limited by the presence of structural lengthwise walls.

Nowadays, after about forty years, 1st PEEP great-size districts are in dramatic situations: buildings live material and performance decay of constructive elements and widespread state of obsolescence. The layout of apartments does not meet nowadays user needs and envelope elements do not ensure energy requirements. The ATER should invest an important amount of funds for managing the asset and for applying apartment retrofitting strategies.

Five case-study buildings have been selected in five different districts constructed in years ranging from 1972 to 1986, with different types of envelope (built on site or prefabricated, with or without thermal insulation) and load-bearing structure (pillars or walls). A total number of 44 types has been studied, covering a total amount of 633 evaluated apartments. In Table 4 the general framework analyzed is displayed and in Figure 5 the selected buildings, with detail photos and plans, are shown within the related urban context. The analyzed buildings are considered long bars, from 5 (CG) to 17 (VN) staircases, except for PIN that presents only two staircases. PIN-building is an a-typical bar that can be classified even as a tower: it is the highest building in the analyzed set arriving up to 12 floors. Buildings have generally two double-sided apartments per floor except for TOR that arrives up to three apartments per floor (with the addition of a central one-sided apartment). Even PIN arrives up to three apartments per floor with a layout similar to tower-buildings with consequent high incidence of non-served areas. Oldest buildings (PP and VN) show a r.c. frame structure while more recent cases (PIN, TOR, and CG), that have been realized with the technique of *coffrage tunnel* and *banches et tables* [88], has a shear wall structure.

3.1. The Case Study of Torrevecchia in Rome

In the present section, a focus, point by point, on the case study of Torrevecchia district is shown. Torrevecchia district was realized starting from the urban project approved in 1978, and buildings were realized between 1979 and 1986. The building stock of Torrevecchia is composed of several buildings (four 15-storey towers, four multi-story bars, two 2-level terraced house lines) converging to a central square, hosting residences, shops and services for a total of 320,000 m^3. One of the four bars is the object of a detailed analysis. The building is composed of 8 staircases units—varying from 4 to 6 levels—with cellars at the ground floor and wash houses on the rooftop. Each Aggregate Module is made up by the reproduction of the same Elementary Typological Module at every story. Each Elementary Typological Module is composed of three apartments per floor.

The proposed method—based on (i) definition of indicators, (ii) creation of the BIM model, (iii) evaluation—is applied to Aggregate Module #2 (MA2), as shown in Figure 6.

Table 4. The five case-study buildings analyzed.

District	Year of Construction	N° of Staircase of the Selected Building	N° of Stories	N° of Types of Apartments	Envelope Type	Structure
Prima Porta (PP)	1972–...	11	5 to 8	6	built on site	r.c. pillars
Vigne Nuove (VN)	1975–...	17	8	12	built on site	r.c. pillars
Pineto (PIN)	1975–1983	2	12	10	prefabricated insulated panels	r.c. walls
Torrevecchia (TOR)	1979–1986	8	4 to 6	4	prefabricated insulated panels	r.c. walls
Castel Giubileo (CG)	1981–...	5	6	12	prefabricated insulated panels	r.c. walls

Figure 5. The five case study districts, with focus on the specific analyzed buildings with photos, and plans.

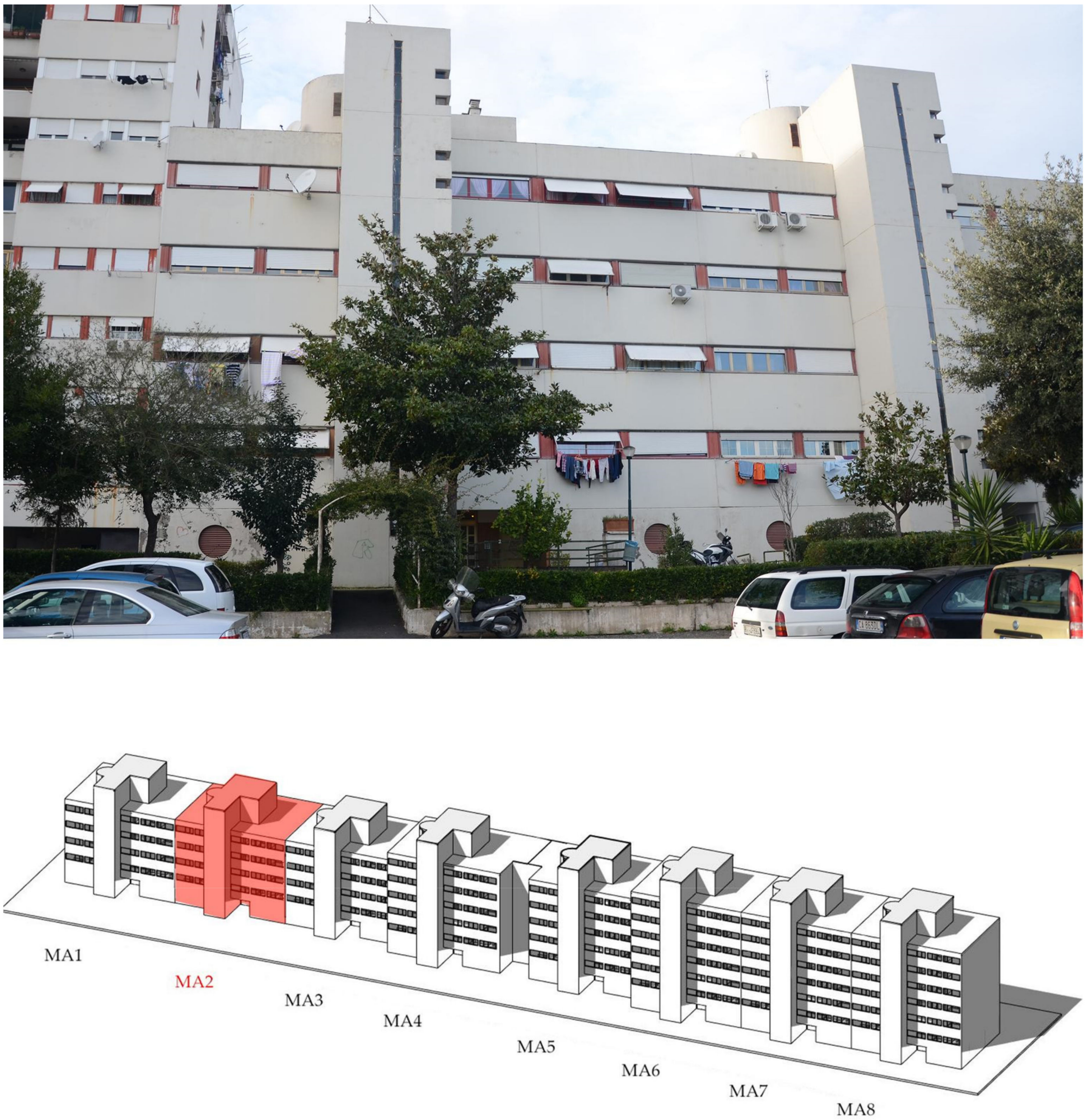

Figure 6. Case-study identification.

1. *Definition of indicators*. The plug-in is focused on dealing with the three criteria *Usability*, *Fragmentation*, and *Constructive modifiability*.
2. *Creation of BIM model.* The BIM model was generated using Revit 2019 by Autodesk. The model has been created based on drawings retrieved from the archive of the ATER Technical Office and the designers' Office.
3. *Evaluation*. Figure 7 shows the results for the apartment. The three pictures highlight elements and areas on which the indicators were calculated in the BIM model. Besides, in Figures 8 and 9, the procedure to obtain the final score evaluation and the #.docx report, respectively, is shown, following several steps. Step 1: the user should click on the button (e.g., Constructive Modifiability). Step 2: a window will open with a short description of indicator and relative formula. By pressing the "Calculation" button, the user will access the drawing area. Step 3: once areas have been created (non-modifiable element total area and gross area), clicking on them is all the evaluator needs to do to generate the evaluation. Step 4: click on the button (e.g., transformability). Step 5: a #.docx report will open showing the obtained normalized results.

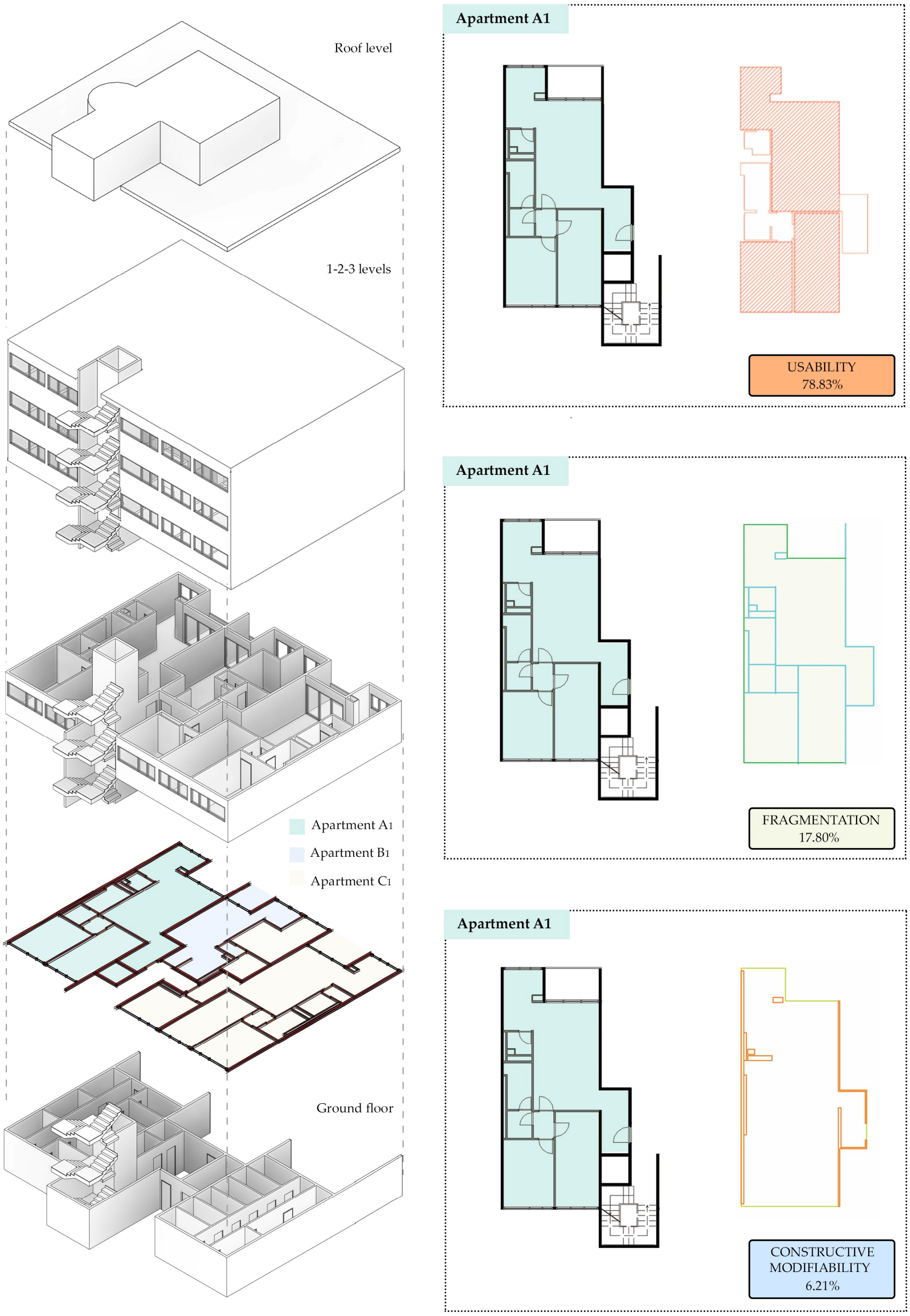

Figure 7. Axonometric cross-section and scores of three indicators.

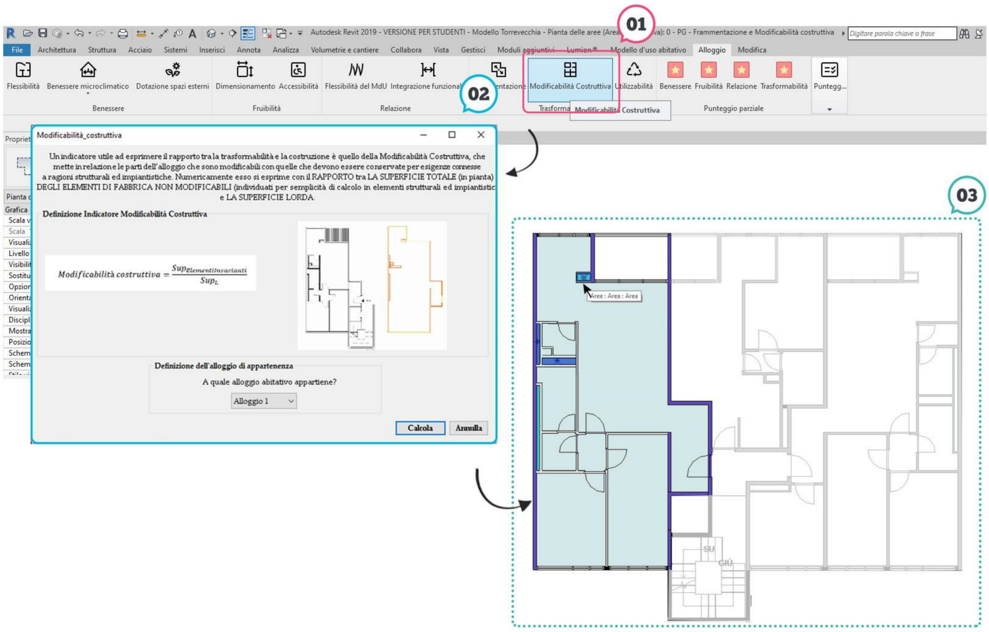

Figure 8. The plug-in user interface in Revit.

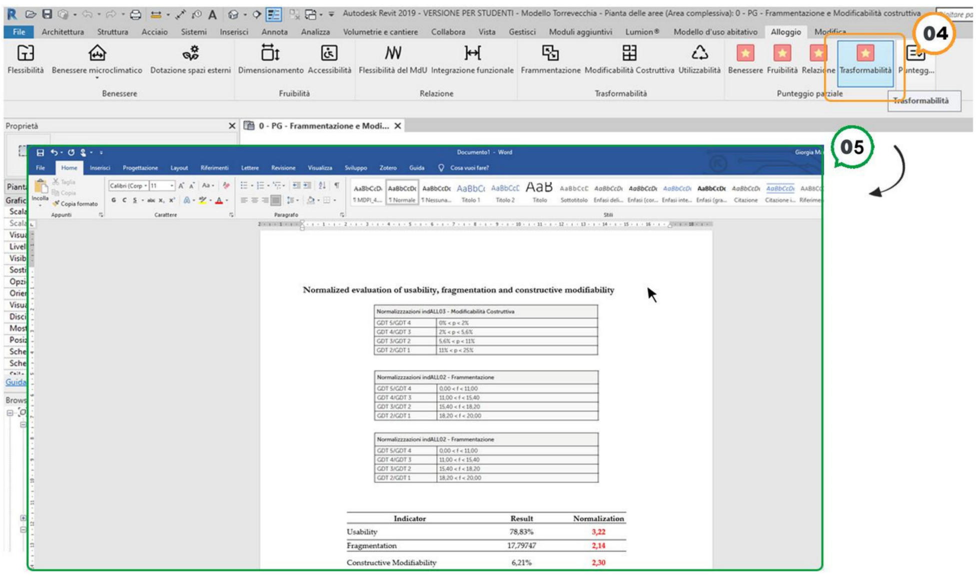

Figure 9. The final #.docx reports.

3.2. Comments of Results

The application of the methodology on the aggregate module MA2 of Torrevecchia reports the following results. Concerning the A1 apartment (see Table 5), this shows a higher transformability related to the usability. The current layout provides more than 20% of the net area for connections. Transformability scores drop due to the high incidence of internal and external walls (equal to 17.80) leading to a fragmentation score of 2.14. The incidence of non-modifiability elements arrives up to 6.21% leading to a Constructive Modifiability score of 2.30.

Compared to the other two apartments of the analyzed MA (see Table 6 and Figure 10), the A1 apartment shows the lowest value of transformability (2.55). The transformability of the B1 apartment arrives up to 3.29, the highest of Torrevecchia. Such a value is determined by the very high fragmentation score equal to 4.33, due to the low incidence of internal and external walls. The C1 apartment shows an intermediate score equal to 3.04.

Table 5. Indicator Scores for A1 apartment.

Indicator	Result	Normalization	Weighting
Usability	78.83%	3.22	0.333
Fragmentation	17.80	2.14	0.333
Constructive Modifiability	6.21%	2.30	0.333
		FINAL SCORE	2.55

Table 6. Transformability Scores for the three apartments studied in Torrevecchia.

Type	Usability	Fragmentation	Constructive Modifiability	Transformability Score
A1	3.22	2.14	2.30	2.55
B1	2.75	4.33	2.78	3.29
C1	2.85	3.57	2.70	3.04

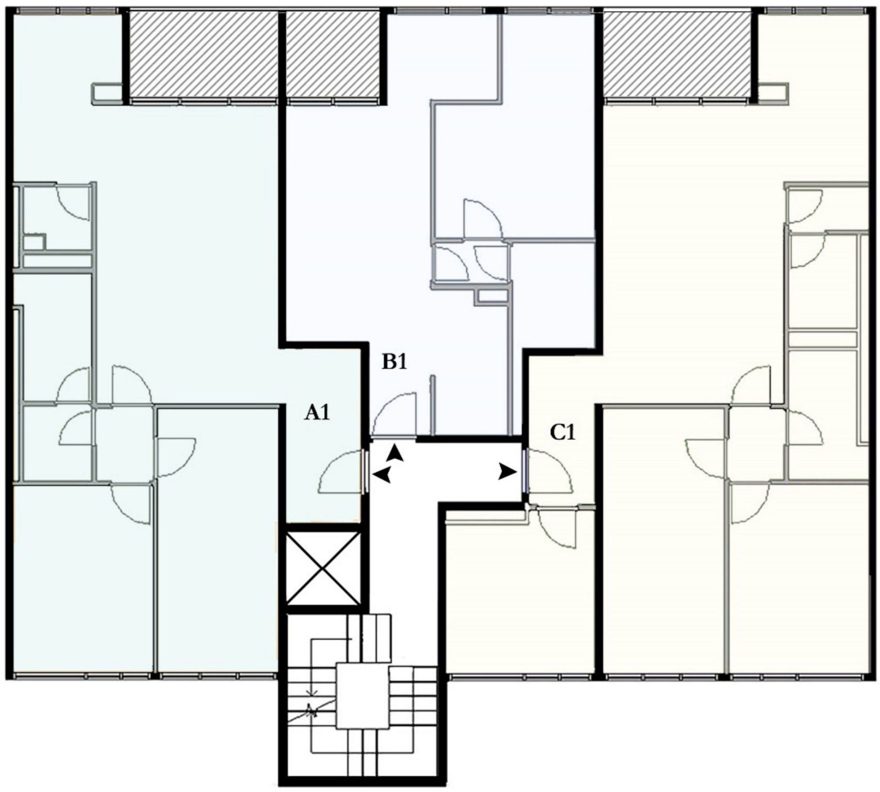

Figure 10. Layout of the three apartments (A1, B1, and C1) analyzed in the Aggregate Module MA2.

The three indicators have been applied on the whole portfolio of the five case studies analyzed, for a total of 44 types and 663 apartments. As highlighted by Figures 11 and 12, gross area values of analyzed apartments is particularly scattered, varying from the 50 m^2 of apartment B1 in Torrevecchia up to the 144 m^2 of apartment P03 of Vigne Nuove. In terms of average values, newer buildings (Torrevecchia and Castel Giubileo) show smaller apartments than older ones, revealing the tendency of 1980s to offer smaller apartments to cope with the reduction of family members per household.

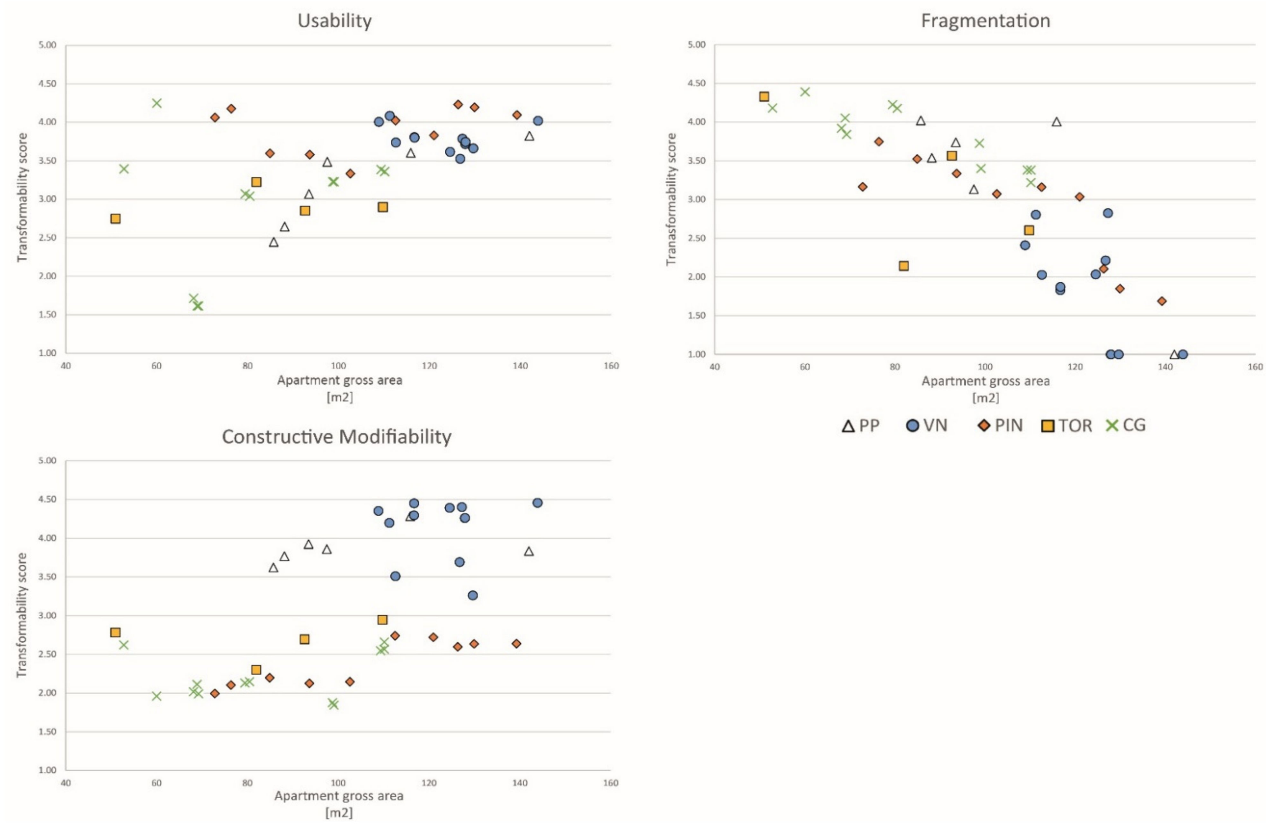

Figure 11. Transformability scores of all the apartments for each indicator: Usability (top left); Fragmentation (top right); Constructive Modifiability (bottom right).

The three indicators provide scatter results in terms of transformability scores (Figure 11). Concerning Usability indicator, PIN and VN-buildings at the as-built state show apartments with high incidence of distribution space and consequently higher transformability scores. Such an indicator is strictly related to the typological configuration of the buildings: in thin and long buildings, apartments designed accordingly to 1960s/1970s' conventional standards (clear separation of apartment zones, large and long corridor, no open spaces) present a strong incidence of distribution spaces. Nowadays, such spaces mean a higher freedom of intervention when layout reorganization is considered. For the Fragmentation indicator, a clear trend in terms of apartment dimensions are shown: smaller apartments prove to have a lower incidence of internal walls (CG and TOR) while in buildings with bigger apartments (VN and PIN above all) the incidence of internal walls is higher, with increasing demolition/reconstruction costs and lower transformability scores. The Construction Modifiability indicator is strictly related to the construction technique with which the building is realized. VN and PP-buildings are realized with r.c. frames with a slight incidence of pillars on apartments' gross area. Such a small value of non-modifiable elements means a higher freedom of intervention when layout reorganization is considered.

In terms of global transformability score (Figure 12), on average the apartments in the two buildings realized with r.c. frames result to be more transformable than apartments in buildings realized with r.c. shear walls. The methodology does not provide absolute values, instead it allows a comparative analysis between apartments of the same asset to define a responsible strategy for sustainable and economic retrofitting. Intervening on more transformable apartments reduces costs of interventions. Buildings realized with the same construction technique (e.g., r.c. frame) differ from each other due to the incidence of internal and external walls and distribution spaces, affecting the fragmentation and the usability score. It is the case of Prima Porta and Vigne Nuove, both realized with r.c.

frame technique. The first one has a higher transformability score depending on the lower incidence of internal walls.

Figure 12. Transformability scores of all the apartments (above), and transformability average values for each case study (bottom).

The average transformability score of Pineto is higher than Castel Giubileo and Torrevecchia, even if it is realized with the same structural technique (shear walls): the typological conformation of the building (a high tower compared to standard bars) amplify the incidence of distribution spaces increasing the transformability score and the related freedom of intervention.

4. Discussion and Conclusions

Due to the need for a more sustainable existing housing stock, it is worthwhile to evaluate the propensity of a building to be transformed. Construction features and architectural layout must be taken into account when assessing renovation scenarios. To date, BIM has been applied to performance assessment and scenarios evaluation at both design and operational phase. It has been outlined that BIM can support decision making especially if integrated with evaluation criteria and systems (as reported in Section 1.1.1). Against such background, this paper argues for an innovative approach to assess dwellings' transformability, by means of a novel plug-in for Revit. The evaluation framework has been described. It is based on the use of a set of performance indicators which have been integrated in a customized application. The arising evaluation tool has been tested on real buildings placed in Rome, Italy. From the results presented above it can be deduced that:

- Apartment's transformability can be quantitatively computed utilizing three indicators concerning usability, fragmentation, and constructive modifiability. Combining these indicators in a single quantitative score allows to compare and to benchmark several apartments within the same typological module, aggregate module or residential organism (Figure 2);
- The proposed Revit plug-in simplifies the evaluation of apartments where it will be suitable to intervene on due to their constructive and typological features. Indeed, such a plug-in allows to automatically assess the transformability of dwellings, and it fastens the evaluation and the comparison of different scenarios (Figures 7–9);
- Apartment transformability is related mainly to the constructive modifiability indicator. Such a score is affected by the building's construction technique. Analyzing the above-mentioned results, buildings realized with reinforced concrete frame structure show higher values of transformability compared to shear wall ones (Figure 12). When buildings are realized with the same construction technique, other indicators impact the final transformability score, such as the fragmentation and usability. Other indicators should be considered when the transformability of the whole building or district is computed and will be analyzed in future work.

The proposed approach is not aimed to define the most effective and convenient strategy in housing retrofitting. Instead, it is specifically aimed to aid stakeholders in comparing their real estate and to support them in choosing the apartment or the building to intervene on. The starting point is the hypothesis that a building with a higher degree of transformability may have lower renovation costs. The failure of some regeneration interventions in peripheral contexts has been the lack of in-depth knowledge of the objects of interventions. Furthermore, the lack of decision-making tools which can help stakeholders to evaluate different redevelopment scenarios and to choose the object to be renovated has been constituting a strong limitation to housing regeneration.

Authors have tested the developed Revit plug-in on real buildings, so that not only the feasibility of the approach has been proved but also the reliability and the validation of the plug-in has been provided.

Quantitative benefits from the application of the proposed tool are currently not available. It has not been used for planning real renovation interventions yet. Additionally, it does not prove, within the limits of this paper, that higher transformability scores lead to lower renovation costs even if this has been considered an assumption of the work. However, it can be said that the developed plug-in allows fast and precise assessment procedures, which otherwise should be carried out manually. This is particularly valuable when a great amount of data, as an entire portfolio, must be managed. In this sense, the added values of this paper are both a conceptual framework for assessing the dwellings' transformability and a BIM-based application to facilitate such an evaluation. The tool is meant to support Public Administrations, asset managers and owners in general, in managing their building stock, indeed.

This research currently focuses only on assessing apartment transformability. The aim is to further expand this evaluation approach and adapt the related tool to the upper levels of the building hierarchy, such as elementary typological modules, the aggregate modules, and the residential organism itself.

Author Contributions: Conceptualization, G.A., L.D., G.M. and R.M.; methodology, G.A., L.D., G.M. and R.M.; software, G.M.; validation, L.D. and G.M.; investigation, L.D.; resources, G.A., L.D., G.M. and R.M.; data curation, G.A., L.D., G.M. and R.M.; writing—original draft preparation, G.A., L.D., G.M. and R.M.; writing—review and editing, G.A., L.D., G.M. and R.M.; visualization, L.D. and G.M.; supervision, G.A. and L.D.; project administration, L.D. Abstract: G.A. and L.D.; Section 1: G.A., L.D., G.M. and R.M.; Section 2: G.A., L.D. and G.M.; Section 3: L.D. and G.M.; Section 4: L.D. and R.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data sharing not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Atanasiu, B.; Despret, C.; Economidou, M.; Maio, J.; Nolte, I.; Rapf, O. (Eds.) *Europe's Buildings Under the Microscope*; Buildings Performance Institute Europe (BPIE): Brussels, Belgium, 2011; ISBN 9789491143014.
2. Italian Ministry of Economic Development. *Bilancio Energetico Nazionale 2017*; Italian Ministry of Economic Development: Roma, Italy, 2018.
3. *United Nations Intergovernmental Panel on Climate Change*; IPCC: Geneva, Switzerland, 2019.
4. D'Alessandro, D.; Dettori, M.; Raffo, M.; Appolloni, L. Housing problems in a changing society: Regulation and training needs in Italy. *Ann. Ig.* **2020**, *32*, 27–35. [CrossRef] [PubMed]
5. Istituto Nazionale di Statistica. *Annuario Statistico Italiano 2019*; Istituto Nazionale di Statistica: Rome, Italy, 2019; ISBN 978-88-458-2003-8.
6. Di Biagi, P.; Marchegiani, E. *Città Pubbliche: Linee Guida per la Riqualificazione Urbana*; Bruno Mondadori: Milan, Italy, 2008.
7. Federcasa e Federcostruzioni: "In Italia Servono 300Mila Nuove Case Popolari". Available online: https://www.federcasa.it/appello-di-federcasa-e-federcostruzioni-in-italia-servono-300mila-nuove-case-popolari/ (accessed on 11 February 2021).
8. Diana, L.; Gissara, M.; Currà, E.; Cecere, C. Tor Bella Monaca and the big dimension: Scenarios of maintenance and regeneration ERP. *Territorio* **2016**. [CrossRef]
9. Rosso, F.; Peduzzi, A.; Diana, L.; Cascone, S.; Cecere, C. A sustainable approach towards the retrofit of the public housing building stock: Energy-architectural experimental and numerical analysis. *Sustainability* **2021**, *13*, 2881. [CrossRef]
10. Scuderi, G. Building Exoskeletons for the Integrated Retrofit of Social Housing. *Civ. Eng. J.* **2016**, *2*, 226–243. [CrossRef]
11. Lamperti, M.; Tsimplokoukou, K.; Lamperti, M.; Negro, P. *Building Design for Safety and Sustainability*; Publications Office of the European Union: Luxembourg, 2014; ISBN 9789279456824.
12. Calvi, G.; Sousa, L.; Ruggieri, C. Energy Efficiency and Seismic Resilience: A Common Approach. In *Multi-Hazard Aprroaches to Civil Infrastructures*; Gardoni, P., LaFave, J.M., Eds.; Springer International Publishing: Cham, Switzerland, 2016; pp. 273–286. ISBN 9783319297132.
13. Marini, A.; Passoni, C.; Belleri, A.; Feroldi, F.; Preti, M.; Metelli, G.; Riva, P.; Giuriani, E.; Plizzari, G. Combining seismic retrofit with energy refurbishment for the sustainable renovation of RC buildings: A proof of concept. *Eur. J. Environ. Civ. Eng.* **2017**, 1–21. [CrossRef]
14. Currà, E.; Diana, L.; Habib, E.; Perno, S. Critical Issues on Integrated Solutions for Seismic and Energy Retrofitting of High-rise Building in Reinforced Concrete Walls and Panels: The M4 in Tor Bella Monaca, Rome. In Proceedings of the SER4SC—Seismic and Energy Renovation for Sustainable Cities, Catania, Italy, 1–3 February 2018; pp. 341–352.
15. Ferrante, A.; Mochi, G.; Predari, G.; Badini, L.; Fotopoulou, A.; Gulli, R.; Semprini, G. A European project for safer and energy efficient buildings: Pro-GET-onE (proactive synergy of integrated efficient technologies on buildings' envelopes). *Sustainability* **2018**, *10*, 812. [CrossRef]
16. La Greca, P.; Margani, G. Seismic and energy renovation measures for sustainable cities: A critical analysis of the Italian scenario. *Sustainability* **2018**, *10*, 254. [CrossRef]
17. Lombardi, D.R.; Porter, L.; Barber, A.; Rogers, C.D.F. Conceptualising Sustainability in UK Urban Regeneration: A Discursive Formation. *Urban Stud.* **2011**, *48*, 273–296. [CrossRef]
18. D'Urso, S.; Cicero, B. From the efficiency of nature to parametric design. A holistic approach for sustainable building renovation in seismic regions. *Sustainability* **2019**, *11*, 1227. [CrossRef]
19. Boeri, A.; Gabrielli, L.; Longo, D. Evaluation and feasibility study of retrofitting interventions on social housing in Italy. *Procedia Eng.* **2011**, *21*, 1161–1168. [CrossRef]

20. Hvejsel, M.F.; Kirkegaard, P.H.; Mortensen, S.B. Towards a Tectonic Approach – Energy Renovation in a Danish Context. *Nord. J. Archit. Res.* **2015**, *1*, 35–60.
21. Lacaton, A.; Vassal, J.-P.; Druot, F. *Plus. La Vivienda Colectiva. Territorio de Excepción [Plus Collective Housing. Territory of Exception]*; Editorial Gustavo Gili: Barcelona, Spain, 2007.
22. Riccardo, F. *Social Housing Renovation. Design Strategies to Improve the Quality of Declining Postwar Multifamily Blocks*; Lap Lambert Academic Publishing: Saarbrücken, Germany, 2011.
23. Reale, L. *Densità, Città, Residenza. Tecniche di Densificazione e Strategie Anti-Sprawl*; Gangemi: Roma, Italy, 2008.
24. Helleman, G.; Wassengerg, F. The renewal of what was tomorrow's idealistic city. Amsterdam's Bijlmermeer high-rise. *Cities* **2004**, *21*, 3–17. [CrossRef]
25. Ferrante, A.; Cattani, E.; Bartolini, N.; Semprini, G. La riqualificazione energetica e architettonica del patrimonio edilizio recente. Il caso dei quartieri di edilizia residenziale pubblica. *IN_BO Ricerche e Progetti per il Territorio la Città e l'Architettura* **2011**, *5*, 251–257.
26. Duinker, M.; van der Torre, M. Osdorperhof—Duinker Van Der Torre Samenwerkende Architecten. Available online: https://www.dvdt.com/project.php?n=3,1,63,78 (accessed on 27 April 2021).
27. Heren 5. De Leeuw Amsterdam. Available online: https://heren5.eu/portfolio/de-leeuw-amsterdam/ (accessed on 27 April 2021).
28. Montuori, M. Good Practices for the Integrated Regeneration of Buildings. In *Eco Districts, Strategies and Techniques for Urban Regeneration in Europe*; Cappochin, G., Botti, M., Furlan, G., Lironi, S., Eds.; Marsilio Editori: Venice, Italy, 2014; pp. 192–203.
29. Kim, E.B.; Somarajan, C. A survey of decision support system applications (1988–1994). *J. Oper. Res. Soc.* **1998**, *49*, 109–120. [CrossRef]
30. Massari, A. *Guida al Nuovo Codice dei Contratti Pubblici. Le Novità del D. lgs. 18 Aprile 2016, n. 50*; Maggioli Editore: Santarcangelo di Romagna, Italy, 2016; ISBN 8891617019.
31. Muhammad, M.Z.; Mustapa, M. A Review of Facilities Information Requirements towards Enhancing Building Information Modelling (BIM) for Facilities Management (FM). *IOP Conf. Ser. Mater. Sci. Eng.* **2020**, *884*. [CrossRef]
32. Diana, L. Metodo CRI_TRA: Un metodo di valutazione comparativa delle criticità e della trasformabilità edilizia del patrimonio residenziale pubblico in Italia. In *L'analisi Multicriteri tra Valutazione e Decisione*; Fattinnanzi, E., Mondini, G., Eds.; Dei Tipografia Del Genio Civile: Rome, Italy, 2015; pp. 273–286.
33. Autodesk App Store. Available online: https://apps.autodesk.com/en (accessed on 4 April 2021).
34. Marmo, R.; Nicolella, M.; Polverino, F.; Tibaut, A. A Methodology for a Performance Information Model to Support Facility Management. *Sustainability* **2019**, *11*, 36–37. [CrossRef]
35. Luciano, A.; Pascale, F.; Polverino, F.; Pooley, A. Measuring age-friendly housing: A framework. *Sustainability* **2020**, *12*, 848. [CrossRef]
36. Re Cecconi, F.; Maltese, S.; Dejaco, M.C. Leveraging BIM for digital built environment asset management. *Innov. Infrastruct. Solut.* **2017**, *2*, 14. [CrossRef]
37. Marmo, R.; Polverino, F.; Nicolella, M.; Tibaut, A. Building performance and maintenance information model based on IFC schema. *Autom. Constr.* **2020**, *118*, 103275. [CrossRef]
38. Bonci, A.; Carbonari, A.; Cucchiarelli, A.; Messi, L.; Pirani, M.; Vaccarini, M. A cyber-physical system approach for building efficiency monitoring. *Autom. Constr.* **2019**, *102*, 68–85. [CrossRef]
39. Shohet, I.M.; Lavy-Leibovich, S.; Bar-On, D. Integrated maintenance monitoring of hospital buildings. *Constr. Manag. Econ.* **2003**, *21*, 219–228. [CrossRef]
40. Matos, R.; Rodrigues, F.; Rodrigues, H.; Costa, A. Building condition assessment supported by Building Information Modelling. *J. Build. Eng.* **2021**, *38*, 102186. [CrossRef]
41. Kazado, D.; Kavgic, M.; Eskicioglu, R. Integrating building information modeling (BIM) and sensor technology for facility management. *J. Inf. Technol. Constr.* **2019**, *24*, 440–458. [CrossRef]
42. Gao, X.; Pishdad-Bozorgi, P. BIM-enabled facilities operation and maintenance: A review. *Adv. Eng. Inform.* **2019**, *39*, 227–247. [CrossRef]
43. Xu, X.; Mumford, T.; Zou, P.X.W. Life-cycle building information modelling (BIM) engaged framework for improving building energy performance. *Energy Build.* **2021**, *231*, 110496. [CrossRef]
44. Reza Soroush, A.A.; Amani, N. BIM-based optimum design and energy performance assessment of residential buildings. *J. Energy Manag. Technol.* **2021**, *5*, 64–72. [CrossRef]
45. Eguaras-Martínez, M.; Vidaurre-Arbizu, M.; Martín-Gómez, C. Simulation and evaluation of Building Information Modeling in a real pilot site. *Appl. Energy* **2014**, *114*, 475–484. [CrossRef]
46. Habibi, S. The promise of BIM for improving building performance. *Energy Build.* **2017**, *153*, 525–548. [CrossRef]
47. He, B.J.; Ye, M.; Yang, L.; Fu, X.P.; Mou, B.; Griffy-Brown, C. The combination of digital technology and architectural design to develop a process for enhancing energy-saving: The case of Maanshan China. *Technol. Soc.* **2014**, *39*, 77–87. [CrossRef]
48. Carvalho, J.P.; Bragança, L.; Mateus, R. Sustainable building design: Analysing the feasibility of BIM platforms to support practical building sustainability assessment. *Comput. Ind.* **2021**, *127*. [CrossRef]
49. Veselka, J.; Nehasilová, M.; Dvořáková, K.; Ryklová, P.; Volf, M.; Růžička, J.; Lupíšek, A. Recommendations for developing a BIM for the purpose of LCA in green building certifications. *Sustainability* **2020**, *12*. [CrossRef]

50. Jalaei, F.; Jrade, A. Integrating building information modeling (BIM) and LEED system at the conceptual design stage of sustainable buildings. *Sustain. Cities Soc.* **2015**, *18*, 95–107. [CrossRef]
51. Angulo, C.; Díaz, K.; Gutiérrez, J.M.; Prado, A.; Casadey, R.; Pannillo, G.; La Rivera, F.M.; Herrera, R.F.; Vielma, J.C. Using BIM for the assessment of the seismic performance of educational buildings. *Int. J. Saf. Secur. Eng.* **2020**, *10*, 77–82. [CrossRef]
52. Welch, D.P.; Sullivan, T.J.; Filiatrault, A. Potential of Building Information Modelling for seismic risk mitigation in buildings. *Bull. N. Z. Soc. Earthq. Eng.* **2014**, *47*, 253–263. [CrossRef]
53. Ambrassa, E.; Comune, A.; Podestà, S.; Diana, L.; Lestuzzi, P. Seismic vulnerability assessment of masonry buildings through BIM. In Proceedings of the IABSE Symposium, Guimaraes 2019: Towards a Resilient Built Environment Risk and Asset Management—Report, Guimarães, Portugal, 27–29 March 2019; pp. 1496–1503.
54. Na, S.; Hong, S.W.; Jung, S.; Lee, J. Performance evaluation of building designs with BIM-based spatial patterns. *Autom. Constr.* **2020**, *118*, 103290. [CrossRef]
55. Shin, J.; Lee, J.K. Indoor Walkability Index: BIM-enabled approach to Quantifying building circulation. *Autom. Constr.* **2019**, *106*. [CrossRef]
56. Kamari, A.; Laustsen, C.; Peterson, S.; Kirkegaard, P.H. A BIM-based decision support system for the evaluation of holistic renovation scenarios. *J. Inf. Technol. Constr.* **2018**, *23*, 354–380.
57. Di Giulio, R. (Ed.) *Suburbanscapes—COST Action TU0701—Improving the Quality of Suburban Building Stocks*; Alinea Editrice: Florence, Italy, 2012; ISBN 978-88-6055-685-1.
58. Piaia, E. Quality assessment of high density housing settlements: Multi-criteria assessment systems and indicators. In *Improving the Quality of Suburban Building stock—Volume 2*; Di Giulio, R., Ed.; UnifePress: Ferrara, Italy, 2012; pp. 181–188.
59. Rostirolla, P. *Ottimo Economico: Processi di Valutazione e di Decisione*; Liguori Editore: Napoli, Italy, 1992; ISBN 9788820722364.
60. Harputlugil, T.İ.; Prins, M.A.; Tanju Gültekin, A.I.T.Y. Conceptual framework for potential implementations of multi criteria decision making (MCDM) methods for design quality assessment. In Proceedings of the Management and Innovation for a Sustainable Built Environment, Amsterdam, The Netherlands, 20–23 June 2011. Available online: http://misbe2011.fyper.com/proceedings/display_manuscript/209.htm (accessed on 11 May 2021).
61. Preiser, W.F.E. Building performance assessment—From POE to BPE, A personal perspective. *Archit. Sci. Rev.* **2005**, *48*, 201–204. [CrossRef]
62. Nicolella, M.; Scognamillo, C.; Pino, A. Multicriteria Analysis for Choosing Maintenance Strategies. In Proceedings of the Seismic and Energy Renovation for Sustainable Cities Conference Proceedings, Catania, Italy, 1–3 February 2018.
63. Balaras, C.; Dascalaki, E.; Droutsa, P.; Kontoyiannidis, S. EPIQR—TOBUS—XENIOS—INVESTIMMO, European Methodologies & Software Tools for Building Refurbishment, Assessment of Energy Savings and IEQ. In Proceedings of the 33rd HVAC Congress, Belgrade, Serbia, 4–6 December 2002; pp. 20–29. [CrossRef]
64. Tersigni, E. Strumenti informatici di supporto alla progettazione per gli interventi di retrofit. In *Retrofit per la Residenza. Tecnologie per la Riqualificazione del Patrimonio Edilizio in Campania*; Ascione, P., Bellomo, M., Eds.; Clean Edizioni: Napoli, Italy, 2012; ISBN 9788884973528.
65. Zijlstra, H. Integrated Plan Analysis (IPA) of Buildings. In *Construction for Development*; Walker, N., Ed.; Document Transformation Technologies cc en CIB: Irene, South Africa, 2007; pp. 686–698.
66. Fattinnanzi, E. La valutazione della qualità e dei costi nei progetti residenziali. Il brevetto SISCo—Prima Parte. *Valori Valutazioni* **2011**, *7*, 49–66.
67. Fattinnanzi, E. La valutazione della qualità e dei costi nei progetti residenziali. Il brevetto SISCo—Seconda Parte. *Valori Valutazioni* **2012**, *8*, 15–38.
68. Whyte, J.; Gann, D.M. Design Quality Indicators: Work in progress. *Build. Res. Inf.* **2003**. [CrossRef]
69. Van der Voordt, T. Quality of design and usability: A vitruvian twin. *Ambient. Construido* **2009**, *9*, 17–29.
70. Università di Bologna. RE.SIS.TO Project. Available online: https://www.resistoproject.com/ (accessed on 16 February 2021).
71. Kamari, A.; Jensen, S.; Christensen, M.L.; Petersen, S.; Kirkegaard, P.H. A hybrid decision support system for generation of holistic renovation scenarios-Cases of energy consumption, investment cost, and thermal indoor comfort. *Sustainability* **2018**, *10*, 1255. [CrossRef]
72. Danilovic, M.; Browning, T.R. Managing complex product development projects with design structure matrices and domain mapping matrices. *Int. J. Proj. Manag.* **2007**, *25*, 300–314. [CrossRef]
73. Artino, A.; Caponetto, R.; Evola, G.; Margani, G.; Marino, E.M. Metodologia per lo sviluppo di un sistema di supporto decisionale per la riqualificazione sismica ed energetica di edifici a struttura intelaiata. In *Proceedings of the Colloquia.AT.e 2020—New Horizons for Sustainable Architecture, Nanjing, China,31 December 2020*; Cascone, S.M., Margani, G., Sapienza, V., Eds.; EdicomEdizioni: Montefalcone, Italy, 2020; pp. 1483–1495.
74. Baffa Rivolta, M.; Rossari, A. (Eds.) *Alexander Klein: Lo Studio Delle Piante e la Progettazione Degli Spazi Negli Alloggi Minimi. Scritti e Progetti dal 1906 al 1957*; Gabriele Mazzotta Editore: Milano, Italy, 1975.
75. Korbi, M.; Migotto, A. Between rationalization and political project: The existenzminimum from klein and teige to today. *Urban Plan.* **2019**, *4*, 299–314. [CrossRef]
76. De Fusco, R. *Storia Dell'Architettura Contemporanea*; Laterza: Napoli, Italy, 1982.
77. Diana, L. Megastructures: A great-size solution for affordable housing. The case study of Rome. *Hist. Postwar Archit.* **2018**, *1*, 72–104.

78. Klein, A. Grundrissbildung und Raumgestaltung von Kleinwohnungen und neue Auswertungsmethoden (Plan design and spatial forms for the minimum dwelling and new methods of enquiry). *Zentralblatt Bauverwaltung* **1928**, *48*, 541–548.
79. Durmisevic, E. Transformable Building Structures: Design for Dissassembly as a Way to Introduce Sustainable Engineering to Building Design & Construction. Ph.D. Thesis, Delft University of Technology, Delft, The Netherlands, 2006.
80. Nuti, F. *Edilizia: Progetto, Costruzione, Produzione*; Edizioni Polistampa: Firenze, Italy, 2010.
81. Galle, W.; Temmerman, N. Multiple design approaches to transformable building: Construction typologies. In *Proceedings of the Portugal SB13: Contribution of Sustainable Building to Meet EU 20-20-20 Targets, Guimarães, Portugal, 30 October–1 November 2013*; Bragança, L., Mateus, R., Pinheiro, M., Eds.; MULTICOMP - Artes Gráficas Lda: Cacém, Portugal, 2013; pp. 783–790.
82. Boaga, G. Un'ipotesi di metodo per la valutazione della compatibilità. In *Flessibilità e Riuso. Recupero Edilizio e Urbano, Teorie e Tecniche*; Alinea Editrice: Firenze, Italy, 1995.
83. Acampa, G. European guidelines on quality requirements and evaluation in architecture. *Valori Valutazioni* **2019**, *2019*, 47–56.
84. Sanguinetti, P.; Abdelmohsen, S.; Lee, J.; Lee, J.; Sheward, H.; Eastman, C. General system architecture for BIM: An integrated approach for design and analysis. *Adv. Eng. Inform.* **2012**, *26*, 317–333. [CrossRef]
85. Acampa, G.; Marino, G.; Ticali, D. Validation of infrastructures through BIM. In *Proceedings of the International Conference of Computational Methods in Sciences and Engineering 2019 (ICCMSE-2019), Rodhes, Greece, 1–5 May 2019*; Simos, T.E., Kalogiratou, Z., Monovasilis, T., Eds.; AIP Publishing: Melville, NY, USA, 2019; Volume 2186, p. 160011. [CrossRef]
86. Acampa, G.; Crespo Cabillo, I.; Marino, G. Representation by drawing against simulation by BIM systems. opportunity or threat for architecture. *Archit. City Environ.* **2019**, *14*, 111–132. [CrossRef]
87. Acampa, G.; Forte, F.; De Paola, P.B.I.M. models and evaluations. In *Green Energy and Technology*; Springer: Berlin/Heidelberg, Germany, 2020; pp. 351–363.
88. Pirera, F. Tecnologie industrializzate. Consorzio Cooperative Costruzioni. Consolidamento delle tecnologie acquisite e innovazioni nelle realizzazioni ex lege 25 a Bologna. *Edil. Pop.* **1981**, *163*, 38–48.