

Case Report

Energy Upgrading of Residential Building Stock: Use of Life Cycle Cost Analysis to Assess Interventions on Social Housing in Italy

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Received: 8 December 2018; Accepted: 2 March 2019; Published: 8 March 2019



Abstract: The debate on the relevance of the global sustainability (including energy, environmental, social, economic, and political aspects) of building stock is becoming increasingly important in Europe. In this context, special attention is placed on the refurbishment of existing buildings, in particular those characterized by significant volumes and poor energy performance. Directive 2012/27/EU introduced stringent constraints (often disregarded) for public administrations to ensure a minimum yearly renovation quota of its building stock. This study describes how Life Cycle Cost analysis (LCC) can be used as a tool to identify the “cost-optimal level” among different design solutions to improve the energy performance of existing buildings. With this aim, a social housing building located in the town of Pisa (Italy) was chosen as the case study, for which two alternative renovation designs were compared using the LCC methodology to identify the optimal solution. The two alternatives were characterized by the same energy performance—one was based on the demolition of the existing building and the construction of a new building (with a wooden frame structure, as proposed by the public company owner of the building), while the other was based on the renovation of the existing building. This study can provide useful information, especially for designers and public authorities, about the relevance of the economic issues related to the renovation of social housing in a Mediterranean climate.

Keywords: Life Cycle Cost analysis; building heritage; economic sustainability; energy upgrading

1. Introduction

Since European Directive 2010/31/EU [1], also known as the directive for the design of “nearly zero-energy buildings”, the concept of the “cost-optimal level” was introduced as a new performance requirement for buildings. The cost-optimal level is used to determine, among several competing design alternatives, the energy performance level which leads to the lowest cost during the life cycle of the building, not only during its use stage. This cost is calculated by the cost-benefits approach and it is determined by taking into account the investment and construction costs, the maintenance and operating costs (including energy savings and earnings from energy produced), and the disposal costs. In January 2012, according to Article 5 of the Directive, the Commission Delegated Regulation No 244/2012 [2] was published, establishing the comparative methodology framework for calculating the cost-optimal levels. Consequently, Member States will have to compare the cost-optimal levels of the minimum energy performance requirements for buildings and building elements (calculated using predefined reference buildings) with the minimum energy performance requirements adopted at

national level. The aim of the comparative methodology is to ensure that the energy performance limits, imposed at national level, are actually effective in terms of life cycle costs. Therefore, any difference of more than 15% among the optimized costs, calculated using the comparative methodology framework and the minimum energy performance requirements in force, must be justified by the Member States.

For the investigations, each Member State must:

- Define the typological and technological characteristics of reference buildings;
- Define the measures/packages/technological variants of energy efficiency;
- Assess the final and primary energy consumption of buildings;
- Assess the costs of the measures/packages/technological variants;
- Generate a consumption-cost curve.

Considering that 78% of Italian building stock was built before the first energy efficiency law (Law 373/76) and 89% before Law 10/91 (the first update of Law 373/76), the energy efficiency of buildings becomes even more crucial for achieving the objectives recently fixed by the Italian Action Plans for Energy Efficiency (PAEE) [3]. PAEE established the objectives for the reduction in the final energy consumption expected for the residential sector by 2020. The report [4], of the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), defined the minimum energy performance requirements for different types of buildings and climatic contexts, and, in this report, the current performance limits for the cost-benefit optimization during the design life cycle are appropriate for residential buildings.

The present study is inserted in the context of the studies concerning the verification of the actual applicability of Life Cycle Cost (LCC) analysis as a tool to evaluate the cost-optimal level. In the study, LCC analysis was used for a social housing building to identify the most cost-effective renovation solution between two alternative designs that were characterized by the same global energy performance—the demolition of the building and the construction of a new building with a wooden frame structure (solution proposed by the public company owner of the building) and the renovation of the existing building.

2. Life Cycle Cost Methodology

A large part of the costs and environmental loads of a building are influenced by the choices made in the design phase [5]. Planning the life cycle of a building (or building elements) becomes imperative to support the decision-making process, and this is demonstrated by the numerous studies in which optimization strategies, based on very different approaches, are developed in the literature, ranging from genetic algorithms to combined Life Cycle Assessment (LCA) and LCC procedures [6–9]. This allows an increased awareness of the burden of both the costs and environmental impacts of alternative technological and design solutions at every stage of the life cycle (from the raw materials supplied for the construction process to the demolition at the end of its useful life) [10–14]. In Italy, the attempts to apply technical-economic evaluations on energy saving strategies are numerous and are not only limited to the building envelope components but also extend to the technical systems, which are designed to maintain comfort conditions [15–17]. For example, in References [18] and [19] a refurbishment design with cost-optimal approaches were applied to Italian school buildings, while in References [20] and [21] similar approaches were applied to residential buildings. However, those that consider evaluation approaches based on LCC are decidedly less numerous. LCC is a management accounting tool for the economic assessment of the choices made in the planning phase [22], and these choices can influence up to 80% of the postconstruction life cycle costs [23].

In March 2006, the CEN (Comité Européen de Normalisation) delegated to the Technical Committee TC 350 the definition of a reference methodological framework to assess the sustainability of the life cycle of buildings [24]. The Working Group 4 “Economic Assessment” worked in this regard to define the EN 15941 standard (“Sustainability of construction works—Assessment of economic performance of buildings—Calculation methods”), completing the methodological framework introduced by EN 15643-4 [25]. This methodological approach takes into account functional

equivalents (equivalent units with the same technical, functional, and performance characteristics), which constitute a basis for the economic evaluation of various design alternatives characterized by using different materials and/or technologies. The comparison must be done on the basis of a chosen Reference Study Period (RSP), which may or may not coincide with the required Design Service Life (DSL) of the building or building element. Based on European standards, the economic performance assessment of a building (or part of it) provides for the systematic collection of data input and output for each phase of the life cycle. With the aforementioned purpose, the system boundaries for the assessment must be clearly identified. Since the analysis of economic sustainability involves different articulate stages of the life cycle (A—product and construction process stage, B—use stage, C—end of life stage, and D—reuse-recovery-recycling potential), modular approaches are usually used. The modular approaches allow the breakdown of the analysis into numerous simple elements by the division of the different stages (A, B, C, D) into submodules, as shown in Figure 1.

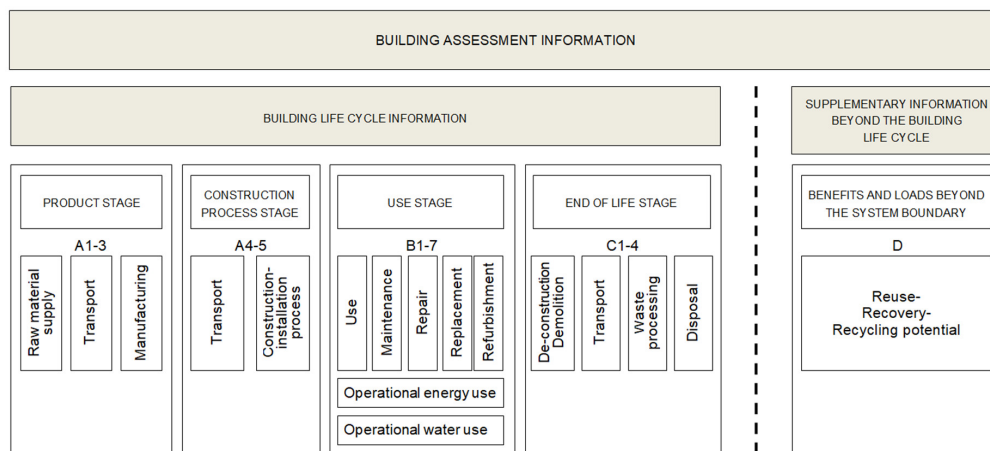


Figure 1. Modular approach for the collection of information in the economic performance assessment of a building [24].

As can be observed from Figure 1, the boundaries from Module A1 to Module C4 cover the economic impacts directly related to the processes that take place within the building life cycle, from production stage to final disposal. Module D quantifies the economic benefits and costs relating to reuse, recycling, and the energy recovery of materials and components that take place beyond the system boundary, for example, their possible reuse as secondary fuels for energy production. Any purchase cost incurred for the site (or any existing building related to activity carried out before the product stage) could be covered by the boundary of an additional module (A0—preconstruction), not shown in Figure 1. It is important to keep in mind that, for each element, the choices relating to the public, economic, and financial variables (taxation system, energy price, cost of capital and resulting discount rate, etc.) strongly influence the economic evaluation. The medium- and long-term scenarios for the energy price trend during the use stage of the building (Module B6), for example, depend on global factors influenced not only by national policy. As a result, this increases the uncertainty in the evaluation of prices along the whole of the use phase. Another important aspect in the economic evaluation is the time chosen for the formulation of the comparative hypotheses. There is a substantial difference between the use of the economic nominal values or the economic real values. The real values are discounted at the time of the valuation using the Net Present Value function (NPV). The discount rate (d) for determining the NPV may also include the interest rate (i) and the inflation rate (a). In this case, d can be calculated with the Fisher equation:

$$d = \frac{1+i}{1+a} - 1 \quad (1)$$

In the present study, the 3% discount rate proposed by Directive 2010/31/EU was chosen. However, in order to verify different scenarios, a fixed inflation rate of 2% and a variation in the discount rate in the 0–15% range were assumed. For example, the choice of low discount rates (less than 3%) is typical of public investors. By contrast, higher discount rates are usually used to meet the investment objectives of private investors. In the application of Life Cycle Cost methodology, which takes into account all the costs associated with the life cycle (including those concerning the end of life stage), the estimation of the residual value of the building or its parts at the end of life cycle is also required. In this study, a life cycle of 50 years was assumed and, at the end of the cycle, both the renovated building and the new one (with a wooden frame structure) were considered as having a realizable value of zero (assuming demolition for both solutions).

3. Case Study Analysis

3.1. Description of Two Alternative Solutions for the Case Study Renovation

The need for improving the energy performance of existing residential building stock involves the scientific and technical community [26,27]. According to the provisions of the European Directives on the energy performance of buildings [1,28,29], each Member State must ensure that a significant percentage of the total floor area of heated and/or cooled buildings, owned by its central government, is renovated (or rather energy upgraded) in order to satisfy the minimum energy performance requirements set in the application of References [1,28,29]. The case study falls within that scope, because it refers to a three-floor row building for social housing (see Figure 2). The building is part of a larger residential complex, built in 1948 in Pisa (district of Sant'Ermete) by the Civil Engineering Department to meet the emergency housing needs for veterans and their families. The building is composed of 12 decrepit apartments and was chosen as a concrete example of social housing inefficiency from an energy performance point of view. The local public company owner of the building (APES company) was planning a main renovation and, at the time, was discussing different design options. The inefficiency of the building is mainly caused by highly dispersive surfaces and old heating systems powered by electricity. The simulation carried out with Edilclima EC7000, a thermal engineering design and simulation software, validated by the Italian Thermo-technical Committee (CTI), shows an energy performance indicator for winter heating (E_{Pi}) of around 300 kWh/m²year for the building, which places it in the worst energy efficiency class, according to the Italian methodology for the energy labeling of buildings [30].



Figure 2. The case study building: (a) North (short side) and East (long side) elevations; (b) South (short side) and West (long side) elevations.

In order to improve the energy efficiency first, as well as the space quality and comfort for users, two alternative solutions for the case study renovation were designed and compared, using different materials and technologies—a first proposal for a conservative renovation and a second proposal for a complete demolition and reconstruction. In the case of demolition and reconstruction, the public company, and owner of the building, was intent on realizing a wooden frame structure building. To meet this need, all assessments were made with respect to this construction technology.

For the first proposal of intervention (Design Solution 1), the strategy adopted has mainly an “additive” character. In fact, new layers and technical elements are added to the existing masonry load bearing walls, while the roof and the ground floor are completely substituted. The renovation project provides a structural consolidation of the brick masonry by means of the technique of static strengthening with a fiber-reinforced polymer (FRP) mesh, due to the poor quality of mortar used in the original masonry. In addition, works on the roof and the ground floor require a selective demolition of part of the building.

For the second proposal (Design Solution 2), the strategy adopted has a “replacement” character and the project involves the complete demolition of the building and its reconstruction with a wooden frame method (platform frame) and wood structural panels (OSB). In this case, the mechanical demolition requires a lower number of construction activities compared with a selective demolition and is, therefore, faster. Advantages in terms of time, compared with the proposal of renovation, also result from the reduction of uncertainty factors related to platform frame technology—the system of production and construction provides tested processes of pre-assembly in the factory and onsite assembly.

Both design solutions lead to a new building with an energy performance lower than 15 kWh/m²year for heating, corresponding to the top energy efficiency class (according to the Italian methodology for the energy labeling of buildings) as requested by the owner of the building. The main actions/measures considered for the two design solutions are summarized in Table 1, while the thermal transmittances of the main building elements (separating the air-conditioned spaces from the outside) are shown in Figure 3.

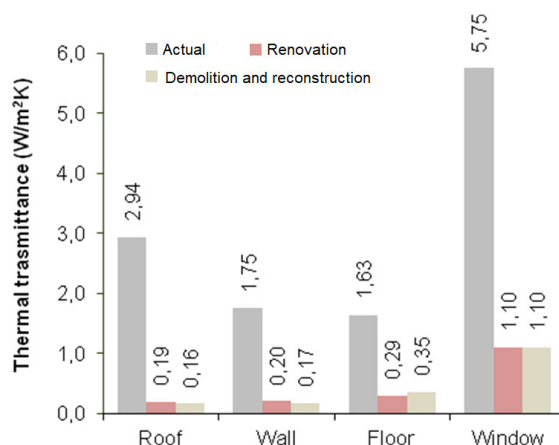


Figure 3. Thermal transmittance of main building elements.

Table 1. Main actions/measures considered for the alternative design solutions.

Conservative Renovation	Demolition and Reconstruction
END OF LIFE STAGE	
Selective demolition	Mechanical demolition
CONSTRUCTION PROCESS STAGE	
Static consolidation	Excavation
Roof replacement and insulation	Substructure
Ground floor replacement and insulation	Rebuilding with Platform Frame method
External wall insulation	Condensing boiler installation
Partition wall insulation	Radiator installation
Window and door replacement	
Condensing boiler installation	
Radiator installation	

3.2. Application of the LCC to the Case Study

In order to apply the LCC, the functional equivalent was defined as 1 m² of row building for social housing, located in Pisa, with a minimum energy performance corresponding to the energy efficiency class A and a period of life established at the design stage (Design Service Life—DSL) equal to 50 years, according to EN 1990 [31].

For the purpose of the global cost calculation for both packages of intervention, the durability of the building was determined, in relation to the different technical solutions provided for the renovation designs. Durability in the life cycle is the period, after construction, during which the building maintains performance levels greater than or equal to the limits required by the project. The definition of durability involves significant methodological and interpretative difficulties. Indeed, the life of a building (or its parts) is not only a function of the theoretical life of materials and elements, but it is also influenced by the boundary conditions that affect the technical and functional performance, such as climate context, intensity of use, quality of services, and possible obsolescence. Unfortunately, reference data on the durability of construction materials under specific conditions of use (Reference Service Life:RSL) are difficult to find. According to the indications of EN 15840 (Annex A), the RSL can be declared in the Environmental Product Declaration (EPD) that covers all the phases of the product life cycle (production, use, maintenance, and demolition) [32]. The RSL value, indicated within the EPD, is referred to as the use envisaged by the manufacturer, which does not always perfectly coincide with the actual use. Different ways for estimating the actual RSL value of building systems and components were developed at a European level [1]:

- A scientific approach, based on the knowledge of degradation phenomena and their actions on materials to define obsolescence models;
- An experimental approach, based on the monitoring over time of buildings or building elements, observing the evolution of degradation phenomena from their first appearance and deriving, from the observed data, effective models of obsolescence;
- A qualitative approach proposed by ISO 15686 [33]. According to Reference [33], the declared RSL value (or the RSL value evaluated by one of the previous approaches) is weighted by opportune correction coefficients to calculate the actual RSL value. Correction coefficients are established for the quality of the components, the design and execution of the works, the specific conditions of the internal and external environment, and the level of use and maintenance. This approach is the most widespread.

Currently in Italy, no useful or detailed information is available for the environmental performance and durability of buildings and building components. In the present study, in order to define the RSL, the international EPD databases, the French INIES database, and the German IBU database were consulted. The RSL value of each building element was chosen equal to the Design Service Life (DSL) for a duration of 50 years, taking into account the residual life of the maintained structures and the EN 15978 standard [34]. Maintenance/substitution plans were designed for both the alternative design solutions, considering the RSL values of the main building elements, as well as plants, windows, and bathroom fixtures. Figure 4 shows the wall maintenance/substitution scenario, as designed for the alternative design solutions. The maintenance, restoration, and substitution costs, according to Figure 4, were computed in the LCC analysis (see Figure 1 also). In order to evaluate the costs properly, the Master Format for Public Construction published by the Tuscany Region (in 2016) was used as the primary source of data, integrated with other sources where necessary. All costs incurred during the building life cycle (operational energy use, demolition and disposal at the 50th year, etc.) refer to current prices, without taking into account the likely changes, due to technological progress, that will be in the RSL.

In Figures 5 and 6, the main cost items considered for the LCC analysis are summarized. Figure 5 refers to Design Solution 1, while Figure 6 refers to Design Solution 2. Specifically, the global costs of the end of life stage for the existing building (LCC A) and the global costs of the construction, use, and end of life stages for the renovated or reconstructed building (LCC B) were defined.

- For Module B6, costs were determined on the basis of the energy consumption for heating and the domestic hot water production during the RSL. The use of cold water and electricity were neglected in the economic assessment, because they are not influenced by the two alternatives analyzed and are, therefore, considered the same for both solutions;
- For Module C, costs were determined on the basis of the project schedule.

It is important to note that, a disposal to landfill of the total waste resulting from a crane and ball demolition at the end of the building life cycle was hypothesized for Design Solution 1. This is because, on the current Italian scenario for recycling, a selective demolition aimed at the separation and recovery of part of the materials would result in economic benefits insufficient to cover even the deconstruction costs alone. Wood fiber insulation was chosen as the thermal insulation material for Design Solution 2. Although it involves higher construction costs, current energy recovery technologies allow a saving of up to 80% of the waste produced by a selective demolition, with subsequent economic benefits from an LCC perspective.

The economic assessment was carried out using the Net Present Value (NPV), as proposed in CEN/TC 350 [24]: “NPV is a standard measure in LCC analyses, used to determine and compare the cost effectiveness of proposed options”. According to this methodology, the future cash flows associated with the different stages of LCC analysis, both incoming and outgoing, are discounted through the use of a selected discount rate. The design solutions have more cash outflows than benefits/revenues, resulting in a negative NPV, which therefore can be defined as the Total Present Cost (TPC). The TPC keeps in consideration all the PC values obtained for each single cost item, according to Equation (2).

4. Discussion

The results of the LCC for Module A (LCC A) and for Module B (LCC B) in both design solutions (renovation (Design Solution 1) and demolition/reconstruction (Design Solution 2), see also Section 3.1.) are shown in Figures 7 and 8. The comparison of LCC A of the two alternatives shows that the activity of deconstruction and selective demolition (required in the case of Design Solution 1) have higher costs than those required for the mechanical demolition (required in the case of Design Solution 2). The processes with the greatest impact on this output data are the roof and ground floor demolition, the removal of plaster, and the use of scaffolding (unnecessary in a mechanical demolition). For both alternatives, the costs for the recovery of the inert materials are evaluated in Module C. However, considering that they can be reused, they lose the classification of waste and, therefore, there will be no costs to incur for disposal and “enter” in Module D. In Module D, the costs refer to subsequent additional treatments to obtain a finished product to be sold for use in the realization of road beds or road embankments. Given that, for Design Solutions 1 and 2, 80% and 95% of the waste volume produced can be respectively recovered, a significant decrease in the overall cost is obtained.

In LCC B, with regard to Module A, the estimated costs for Design Solution 2 are greater than those needed for Design Solution 1. However, Design Solution 2—for which mortar and liquid binder are not employed, only dry connection systems (wooden frame structure)—allows a considerable acceleration of the construction process. In the case of Design Solution 1, the construction costs account for 59% of the overall cost while those attributable to the use stage (Module B—sum of B2, B3, B4, and B6) account for 33%. In the case of Design Solution 2, the construction costs rise to 64% while the use costs (Module B) come down to 29%. Based on the definition of the functional equivalent, the use costs are similar for both design alternatives. The most significant items are the annual energy consumption and the restoration of the internal and external wall paint, which must be carried out every ten years according to the maintenance and replacement plan. The costs of demolition and waste disposal at the end of the life cycle (Module C) are lower for Design Solution 2 compared with Design Solution 1. This is because the wood will be reused as a secondary fuel for energy production. In addition, the economic benefits arising from the wood recovery in dedicated biomass power plants are difficult to quantify and predict. As mentioned in previous sections, the demolition of the building

is the end of the life cycle, therefore, no residual value was foreseen for either design solution. In the case of masonry buildings (Design Solution 1), the durability (RSL) was set to 100 years. Moreover, considering that the building was built in 1948 and that about 60 years had elapsed at the time of the intervention, it is assumed that at the end of this cycle it will have to be demolished, because it will no longer be suitable for further renovations. In the case of the wooden frame structure (Design Solution 2), the durability (RSL) was set to 50 years. This value is much lower than the RSL value suggested from experience for the specific frame structure (RSL is about 80 years for wooden frame structure buildings); however, a significant reduction of RSL can be considered for buildings intended for social housing, due to the poor care and attention that the users pose during the operative life of this type of building.

Finally, the trend of the TPC for the discount rate is shown in Figure 9 for the alternative design solutions. From Figure 9, the convenience of Design Solution 1 compared with Design Solution 2 can be observed, regardless of the considered discount rate.

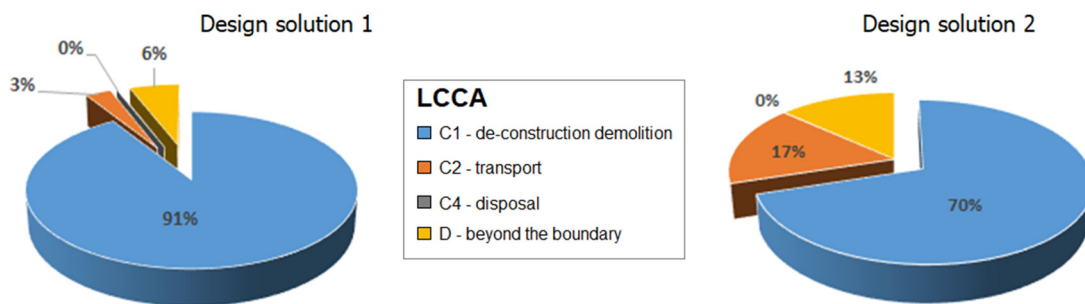


Figure 7. Comparison of LCC A results for the alternative design solutions.

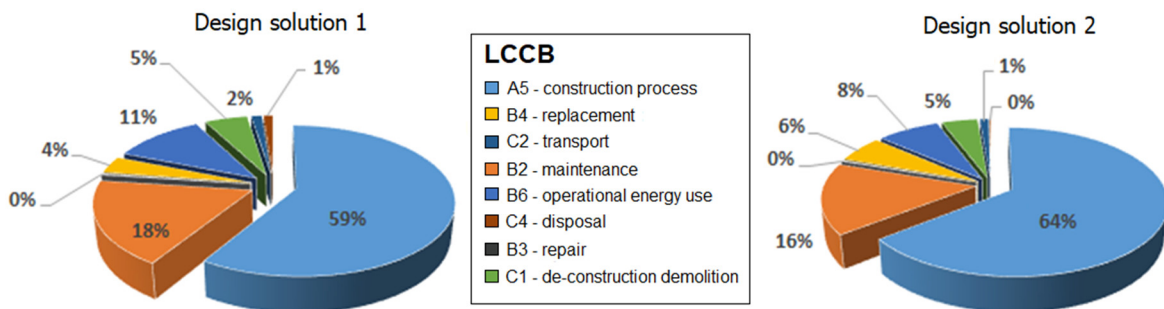


Figure 8. Comparison of LCC B results for the alternative design solutions.

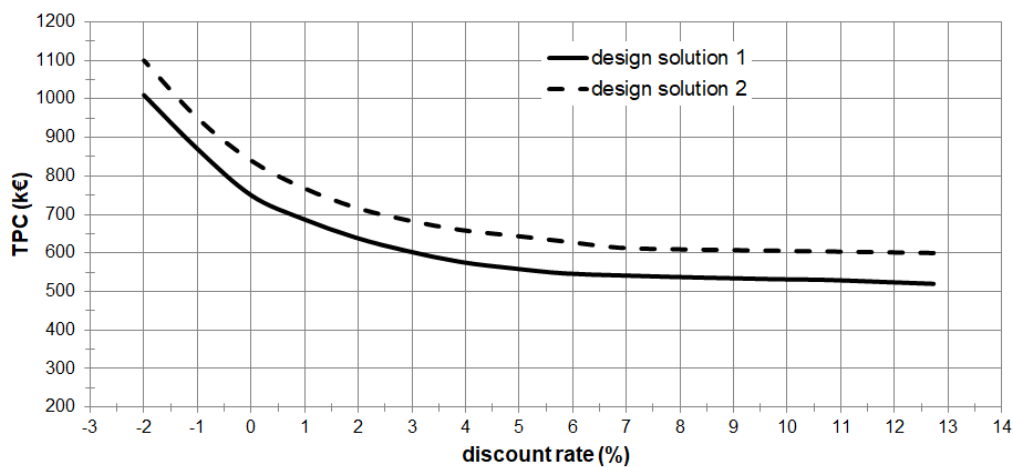


Figure 9. Trend of Total Present Cost (TPC) for the discount rate.

5. Conclusions

The assessment of the economic sustainability of the competing design solutions conducted with the Life Cycle Cost analysis is, in essence, a method which makes the design process more complete, structured and, therefore, conscious in order to guide investors in their decisions. Especially in the building renovation sector, investors are driven by speculative criteria based mainly on the construction costs and often neglect the use and maintenance costs. These latter costs acquire strong importance when the investor also manages the building, as usually happens for public administrations.

In the present study, the LCC analysis was used for a social housing building to identify the most cost-effective renovation solution between two alternative design solutions characterized by the same global energy performance—the demolition of the building and the construction of a new building with a wooden frame structure (a solution proposed by the public company owner of the building) and the renovation of the existing building. From the accurate analysis conducted by the authors, the convenience, in terms of total present cost, of the existing building renovation (Design Solution 1) emerged compared with the demolition and reconstruction (Design Solution 2). This convenience was confirmed regardless of the considered discount rate. Specifically, applying the LCC to the end of life stage for the existing building, it was possible to observe that the activity of deconstruction and selective demolition (required in the case of Design Solution 1) would have higher costs than those required for the mechanical demolition (required in the case of Design Solution 2). However, when the LCC was applied to the construction, use, and end of life stages for the renovated or reconstructed building, the estimated costs for Design Solution 2 were greater than those needed for Design Solution 1. In the case of Design Solution 1, the construction costs (a more significant cost item) account for 59% of the overall cost while those attributable to the use stage account for 33%. In the case of Design Solution 2, the construction costs rise to 64% while the use costs come down to 29%.

In order to give a decisive boost to the energy upgrading of existing buildings, Italy should align itself with the other European countries, not just in response to European directives but also to act against climate change. To do this, it should promote the use of LCC and LCA analysis, and, above all, it should implement national databases and make them easily accessible to facilitate the exchange of knowledge and information between all the operators engaged in renovation design. Case studies, such as the one dealt with by the authors in this study, are useful application examples for both designers and investors (in particular public administrations), disseminating well-structured approaches to guide conscious decisions, which aim to improve the environmental and economic sustainability of the building stock.

Author Contributions: All the authors contributed in equal parts to the research activity and to the paper writing.

Funding: This research was partially funded by APES, a company with public participation for the management of social housing in the Pisa District (Italy).

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of the data; in the writing of the manuscript; or in the decision to publish the results.

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