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Concrete Self-Healing for Sustainable Buildings: A Focus on the Economic Evaluation from a Life-Cycle Perspective

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Abstract: Concrete is one of the world's most used and produced materials, based on its dominant role in the construction sector, both for the construction of new structures and for the repair, restoration, and retrofitting of built ones. Recently, research has been focused on the development of innovative solutions to extend the service life of reinforced concrete structures, specifically by introducing self-healing properties aimed at reducing the necessary maintenance interventions and, consequently, the environmental impacts. These solutions imply costs and financial feasibility impacts, which must be measured and evaluated to support the ranking of preferable alternatives. Thus, this paper proposes a methodology capable of supporting the selection of material/product options from the early design stages in the construction sector. Assuming a life-cycle perspective, the Life-Cycle Costing (LCC) approach is proposed for comparing three material solutions applied to the case study of a wall component hypothesized to be used in building construction in Turin, Northern Italy. Namely, traditional standard concrete and two different self-healing concrete types were evaluated using the Global Cost calculation of each solution. The focus is on the material service life as a crucial factor, capable of orienting investment decisions given its effects on the required maintenance activities (and related investments) and the obtainable residual value. Thus, according to a performance approach, LCC is combined with the Factor Method (FM). Assuming the capability of the lifespan to affect the Global Cost calculation, the results give full evidence of the potential benefits due to the use of self-healing materials in construction in terms of the reduction in maintenance costs, the increase in the durability of buildings and structures and related residual values, and consequently, the reduction in the environmental impacts.

Keywords: economic–environmental sustainability; self-healing concrete; 3D-printed capsules; macro-capsules; Life-Cycle Costing; Factor Method; service life

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1. Introduction

Concrete is one of the preferred solutions for construction for its large availability, not high cost, and mechanical characteristics, such as the intrinsic high capability to resist compressive stresses and the synergic compatibility with steel reinforcement to sustain tensile stresses. Undoubtedly, the introduction of reinforced concrete has revolutionized the history of architecture and engineering.

The current environmental crisis due to climate change is strictly linked to negative effects such as excessive CO_2 emissions, water pollution, waste production, and many other factors. In this framework, the intensive production and use of concrete is a crucial issue, precisely due to the consumption of natural resources and fuels for production. Elevated rates of CO_2 emissions are also connected to the production and use of concrete due to the

calcination of natural limestone and clay in cement plants, the fuel combustion for clinker burning and grinding operations, and the emissions caused by concrete manufacturing and transport. Concrete waste production and disposal at the end of a structure's service life represent, in turn, a crucial environmental problem. The construction sector represents about 25–30% of all waste produced in the EU [1,2], including different materials such as concrete, plastic, wood, glass, metals, etc. Almost all the mentioned materials can be recycled in principle but are not in practice for many reasons.

Thus, the research demand for growing knowledge about alternative and improved materials caught the interest of researchers in the current debate on this topic. Many promising studies focus on extending the concrete lifespan based on self-healing strategies [3,4], either (stimulated) autogenous [5–8] or autonomous [9–12] healing. Among these, many have highlighted the potential of capsule-based self-healing for autonomously filling of cracks (which originate during usage) with different types of repairing agents. These studies focused on the use of both micro- [10,13–15] and macro-encapsulation [16–20], while the investigated repairing agents were minerals, polymers, or bacteria [17,21–29]. Crack sealing can prevent the exposure of steel rebars to detrimental environmental conditions, thus reducing the consequent risk of corrosion of the reinforcement. As is known, reinforcement corrosion is one of the main factors responsible for the deterioration of structural performance, eventually leading to premature collapse. Accordingly, as emerged from the literature, self-healing concrete can also positively impact the concrete lifespan, reducing maintenance interventions and environmental impacts [30,31].

According to the economic viewpoint, positive impacts are expected when using self-healing concrete in building construction due to reduced maintenance activities and related costs and lower investments for repairing and replacement. Consequently, the financial feasibility of projects can be positively impacted in terms of profitability, thus catching the interest of real estate developers and designers in adopting this innovative technology. Moreover, previous research shows that components' durability and relative service life are capable of altering the output of the economic method application and the estimated residual values [32]. The results of LCC applications prove that the lifespan is capable of influencing the global cost, exceeding, in some cases, environmental and even financial element effects.

Despite the high importance of the potential effects on real estate market dynamics, the impact of self-healing concrete on the economic sphere and sustainable design has to be further analyzed, considering the present scarcity of the literature. Thus, this paper aims to propose a methodology for quantifying the economic impact of concrete self-healing production and use and, according to a decision-making perspective, for supporting the comparative selection among alternative materials/products from the design stages. Additionally, the focus is on the component service life as a relevant item, capable of orienting investment decisions given its effects on durability, the maintenance activity required, and the potential residual value. Attention is mainly paid to service-life estimation and its effects on the global cost and residual-value calculation.

Operatively, assuming a circular perspective, the Life-Cycle Costing (LCC) methodology [33] is proposed for comparing different material solutions—traditional concrete and two alternative self-healing concrete types—applied to the case study of a wall component, which is hypothesized to be used in building construction in Turin, Northern Italy. LCC is solved using the Global Cost calculation of each solution. According to a joint modality, the LCC approach is combined with the Factor Method (FM), standardized using ISO 15686—part 1:2000 [33]. This second approach is included to support the service-life prediction of a building component with the quantification of its service life by multiplying its Reference Service Life (RSL) with a list of factors, opportunely weighted, capable of influencing the component durability, according to a performance approach. A group of sub-factors is introduced to enhance the model; then, the results of the previously conducted laboratory tests are used to opportunely assign a weight to each sub-factor. Further, to introduce flexibility into the models, considering the presence of uncertainty due to the data variability

and the limits of the simulation, the analysis is conducted by adopting a double scenario (high impact and low impact).

The simulation results demonstrate the capability of a lifespan to perturb the global cost and specifically highlight some potential benefits of using self-healing materials in construction to reduce maintenance costs, increase the lifespan of structures, and, consequently, reduce environmental impacts.

The innovative application proposed in this work contributes to extending the scientific literature on the topic and represents a step forward in future field applications of self-healing concretes. Practical implications are in the private and public interventions and Public Private Partnership (PPP) operations. Thus, this research is addressed to both private and public subjects involved in different phases: (1) private subjects in the selection of the best design options (considering the economic–financial feasibility of projects on different scales and with the adoption of different construction materials); (2) public subjects in decision-making processes based on the economic impact of project options and based on the environmental sustainability, for example, in the development of Green Public Procurement/Sustainable Public Procurement processes.

This paper is articulated as follows: Section 2 presents the literature and regulatory background. Section 3 illustrates the methodological background. Section 4 presents the case study. Section 5 shows the results of the analysis. Finally, Section 6 contains the main conclusions and final remarks.

2. Literature Background and Regulatory Framework

Besides the studies on self-healing cementitious materials mentioned in the previous section, this work is founded on a double scientific background. On one side is the LCC approach, and on the other is the Factor Method. Both approaches are recognized internationally among other fundamental tools, as demonstrated by the growing scientific literature covering their methodological aspects and applications. Among the contributions, references and regulations—enforced to implement environmental policies at the European and international levels—are used as fundamentals in this paper.

LCC analysis is normed using Standard ISO 15686:2008, Buildings and constructed assets—Service-life planning, particularly Part 5: Life Cycle Costing, prepared by Technical Committee ISO/TC 59, Building construction, Subcommittee SC 14, Design life [33]. As illustrated in Section 3, this Standard is the methodological foundation for LCC analysis. The methodological foundation of LCC is the Global Cost calculation, defined in Standard EN 15459:2007—Energy performance of buildings—Economic evaluation procedure for energy systems in buildings [34], and related Guidelines accompanying Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012 supplementing Directive 2010/31/EU [35]. Starting from the fundamental contributions on the topic [36–43], researchers have explored the approach in the Italian context and using applications. See, for example, [44–48].

In a joint perspective with the LCC, the FM is normed by ISO 15686-8:2008, Building and constructed assets—Service Life Planning, Part 8: Reference Service Life and Service Life estimation [49]. As illustrated in Section 3, this Standard is the methodological foundation for the Factor Method application, and, with specific reference to the Italian context, it is strictly correlated with the document UNI 11156-3: 2006, "Valutazione della durabilità dei componenti edilizi". Metodo per la valutazione della durata (vita utile)" (Evaluation of the durability of building components, i.e., the durability assessment method (service life) [50]. As the norms emerge, the FM is a tool for supporting the durability estimation, assuming a certain number of Reference Service Lives (RSL) as the reference values. Despite the difficulty in its prediction, service life estimation is a fundamental step in LCC applications, particularly in maintenance cost assessment. Further, the EU guidelines and regulations also norm the building products' durability requirements. As demonstrated in the literature, the RSL and the Estimated Service Life (ESL) can be quantified using a set of different approaches, which can be reconducted to the following groups [51–63]:

- Methods based on expert opinion, experience, and knowledge about the component behavior.
- Methods based on scientific research, laboratory tests, statistical analysis, and technological information by producers.
- Methods based on the deterministic and/or probabilistic application of the FM.
- Method based on the engineering approach. Among these, the engineering of the FM, oriented to reduce the subjectivity of the simple FM, proposes an operative modality based on performance-based grids composed of the characteristics of the building component capable of impacting its durability and, consequently, the residual value of components [64–67], as will be illustrated in the following methodological section.

Finally, a fundamental contribution to this present research derives from the work by the authors of [68]. In this work, the authors explore the economic and environmental sustainability of innovative material solutions experimented with mitigating cracks in reinforced concrete via superabsorbent polymers. They apply Life-Cycle Assessment (LCA) and LCC to compare alternative solutions from a life-cycle perspective. The behavior in the lifespan and effects on the durability, according to the maintenance activity, are considered in the evaluation, with results that demonstrate the economic and environmental advantages particularly relevant in long time horizons. Then, in work [69], the development of innovative prefabricated concrete elements to be used in the energy retrofitting of existing buildings is explored under the economic–environmental viewpoint using the environmental LCC approach. The focus, in this case, is on the detection of the effects of specific cost items on the analysis results from a cost-optimization perspective and on the influence of discount rate on the result calculations.

Both works, with other contributions [70–75], represent the recent literature contributions oriented to harmonizing the economic sustainability of alternative materials, assuming a life-cycle and environmental perspective, as in this research.

3. Methodological Background

The methodology proposed in this study is founded on the joint application of two approaches. The LCC approach is calculated using the Global Cost method, its main synthetic indicator, and the deterministic FM with the performance grid approach elements for modeling alternative options' service life. According to the methodological aspects below, the methodology is implemented using a four-step workflow.

3.1. Economic Evaluation with LCC Analysis

The selection of the preferable solution among alternative technological scenarios is supported using the Life-Cycle Costing (LCC) methodology, normed with ISO 15686-5:2008 (revised July 2017—ISO 15686-5:2017) [33]. As illustrated in the vast literature on this topic, this approach can quantify short- and long-term costs and benefits by calculating the synthetic indicators, assuming the entire life cycle of alternative scenarios (technological solutions). The efficiency and effectiveness of project options are evaluated according to a circular perspective. LCC is a tool to evaluate alternative products for new build constructions or retrofitting interventions, assuming a "from the cradle to the grave" perspective. The Global Cost concept, upon which LCC is founded, is defined in Standard EN 15459:2007 (repealed in Standard EN 15459:2017) [34]; synthetizing, it can be formalized as shown in Equation (1):

$$C_G(\tau) = C_I + \sum_j \cdot \left[\sum_{i=1}^{\tau} \left(C_{a,i}(j) \cdot R_d(i) \right) - V_{f,\tau}(j) \right] \quad (1)$$

where $C_{G(\tau)}$ stands for the global cost (referred to as starting year τ_0); C_I stands for the initial investment costs; $C_{a,i}(j)$ stands for the annual cost during the year i of component j, which includes annual running costs (energy costs, operational costs, and maintenance costs), periodic replacement costs, and dismantling and disposal costs; $R_d(i)$ stands for discount factor during the year i; and $V_{f,\tau}(j)$ stands for the residual value of the component

j at the end of the calculation period, referred to the starting year. The discount factor R_d is formalized as in Equation (2):

$$R_d(p) = \left[\frac{1}{1+\frac{r}{100}}\right]^p \quad (2)$$

where p stands for the number of years starting from the initial time, and r stands for the real discount rate. Notice that the initial investment costs are not discounted.

This research proposes a simplified LCC application at the material scale, focusing on maintenance cost items and service lives/residual values comparative analysis, as described below. The simplified Global Cost model adopted in this study is formalized in Equation (3):

$$C_G = C_I + \sum_{t=1}^{N} (C_m)/(1+\mathrm{r})^t + (V_r)/(1+\mathrm{r})^N \quad (3)$$

where C_G stands for the Global Cost, C_I stands for the investment costs, C_m stands for the maintenance cost, V_r stands for the residual value, t stands for the year in which the cost occurred, N stands for the number of years of the entire period considered for the analysis, and r stands for the discount rate.

3.2. Service Life Estimation via the Factor Method with Sub-Factors

In the LCC model, a very delicate step is the residual value calculation, which, in turn, depends on the analysis period set given the component service life estimation. The FM, as illustrated in ISO 15686—part 8, is proposed to model the component's lifespan. In the Standard, the FM, according to a "performance approach", is proposed to quantify the service life of a component of a building by multiplying its RSL by a set of seven factors capable of impacting its durability, assuming certain conditions, as formalized in Equation (4):

$$\mathrm{ESL} = \mathrm{RSL} \times \mathrm{A} \times \mathrm{B} \times \mathrm{C} \times \mathrm{D} \times \mathrm{E} \times \mathrm{F} \times \mathrm{G} \quad (4)$$

where ESL stands for the component estimated service life, RSL stands for the reference service life, A stands for the quality of materials and components, B stands for the design level, C stands for the work execution level, D stands for the indoor environment conditions, E stands for the outdoor environmental conditions, F stands for the in-use conditions, and G stands for the maintenance level. Each factor of the equation has to be evaluated for each specific application based on laboratory experiments, tests, simulations on specific components, or simulations based on data deducted from scientific publications. The method can be enhanced by introducing a set of sub-factors related to each factor in Equation (4). Then, these sub-factors can be linearly combined to represent the synthetic factors indicated in the equation. Each sub-factor is introduced to highlight the elements able to impact the degradation process, improve/diminish the performance of the material/component, and, in general, influence its durability. The "factor grid", which derives from this operative modality, can be a modality to prefigure the component performances over time. Thus, a performance analysis over time and critical value identification for each variable (critical performance) is required. The minimum critical value obtained represents the service life.

In this work, a hypothesis of the factors' entity is assumed according to the following consideration: design level, execution level, indoor environment conditions, outdoor environmental conditions, and in-use conditions are considered equal. Contrarily, specific sub-factors associated with the factor representing the materials' quality and components (factor A) and the maintenance level (factor G) are assumed, according to the results of the laboratory tests preliminarily developed on a set of optional components.

In summary, the analysis workflow for the estimated service life quantification via the FM is as follows:

- Step 1: Individuation of the RSL of each component based on the literature on the topic and related data.
- Step 2: Individuation of the factors/sub-factors for FM application, according to a simplified performance approach implementation. This second step focuses on

estimates based on empirical laboratory tests and the sub-factors weighting the set of alternative scenarios.
- Step 3: Internalization of estimated service lives in LCC analysis and application for each alternative scenario.
- Step 4: Comparison of results.

4. Case Study

A case study is adopted as a reference for applying the previously mentioned methodology. The results of a research experience, "Evaluation of Concrete Self-Healing Systems Using Capsule Strategies: A Comparative Case Study", conducted by [76], are employed.

The mentioned work focuses on implementing self-healing strategies based on the development of novel types of macrocapsules (>1 mm) and their incorporation into cement-based materials. More specifically, it evaluates the performance of self-healing mortars obtained via the addition of two different types of capsules: tubular capsules with 3D-printed polylactic acid shells containing a polyurethane expanding resin as the healing agent and virtual capsules formed by compacting an active powder mix at (relatively) high temperatures (260 °C), subsequently coated with an epoxy resin (Figure 1) [76]. This study evaluates the performances of the two mortar systems (PLA and VIR, respectively) compared with a standard cement mortar (referred to as CEM) in terms of initial resistance, strength recovery, and crack-sealing capacities. Mortar prisms were used as specimens to quantify the performances at the lab scale.

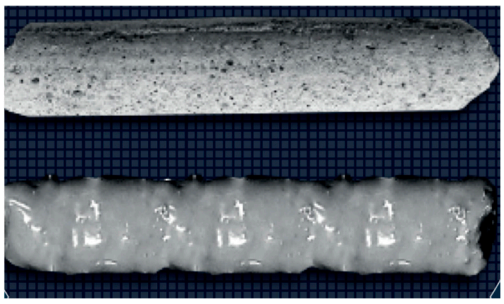

Figure 1. Virtual capsules: uncoated (on **top**), with the epoxy coating (**below**) (diameter is approximately 1 cm; length is about 5 cm).

The following steps were carried out:

(1) Self-Healing Capsule Development. The first type of capsule was developed by optimizing the design of a 3D-printed PLA tubular shell (with a tensile strength of 100 MPa and an elastic modulus of 3.5 GPa [77]) in combination with a commercial epoxy resin sealing (Stucco K, API SpA) in order to encapsulate a highly moisture-reactive, polyurethane(PU)-based, expansive healing agent (Carbostop U, Minova S.p.A.) [78]. A similar healing agent had already been investigated by the authors' research group in [9], revealing the excellent potential for self-healing applications. According to the safety and technical datasheet of the resin Carbostop 102, which is similar to the Carbostop U that we used (both react with ambient water and yield a polyurethane/polyurea foam) [79], the PU resin is not a flammable liquid but can burn when in fire. However, a capsule content of about 4 vol% is targeted [19] to not decrease the mechanical properties of the self-healing concrete. When the capsule is broken, the PU resin is released and expands in cracks, usually with a size smaller than 1 mm, and seals them. Then, the availability of oxygen in the closed cracks is expected to be limited below the external surface of the repaired concrete. Thus, the risk in case of fire can be considered limited. However, the used PU resin is designed for underground engineering, and its resistance to fire obviously needs to be assessed. A summary of the research conducted on the fire performance of

monocomponent PU adhesives for engineered wood products is proposed in the work of Shirmohammadii et al. [80]. As these materials must comply with the EN 301:2023 [81] and EN 302:2023 [82] standards, they tend to form a charred layer that slows down the combustion rate. Similar products can be used for self-healing concrete, too. However, some important drawbacks can be associated with the use of mono or bi-component organic healing agents (such as polyurethane resins), and in particular, the potential loss of effectiveness in the case of late-age cracking due to the relatively reduced the shelf life of these families of chemicals. For this reason, a new healing agent was developed, and a second type of capsule was designed accordingly. To this aim, an active powder mix was investigated that comprised a 10:1:1 proportion of a commercial mortar for restoration (Rassasie rapid cement, made of CEM II 32.5 R (cement with lime), quartz sand and admixtures, with a pot life of 2 min. When mixed with 23–25 parts of water, the compressive strength at 28 days should be 40.5 MPa [83]), used as the healing agent; sodium polyacrylate (a superabsorbent polymer), used as an internal curing agent to favor cement hydration; and an acid-base mix (containing sodium bicarbonate, malic acid, and tartaric acid for the production of sparkling water), used as an expanding agent. "Virtual capsules" were then created by compacting the powder mix at high temperatures in the shape of small cylinders and, subsequently, coating them with a commercial epoxy resin (Plastigel 3220, API S.p.A.).

(2) Experimental Setup. This study employed mortar prisms with the addition of the two above-described types of capsules (denoted as PLA and VIR, respectively) and reference mortar prisms without capsules (labeled CEM). The prisms were subjected to three-point bending tests using a 250 kN closed-loop servo-controlled MTS hydraulic press. The applied force was measured in kiloNewtons (kN), and a sensor beneath the prism recorded the crack opening (crack mouth opening displacement, CMOD; Figure 2). The maximum load was determined, representing the force that the prism could withstand. After cracking, the samples were allowed to repair autonomously underwater for 8 and 18 days. Then, they were tested following a water-flow test set-up to evaluate their self-sealing capacity and again under a three-point bending test set-up to evaluate the eventual mechanical strength regained after self-repair.

(3) Results and Analysis. This study compared the performance of the prisms under stress, with a focus on the initial resistance, strength recovery, and crack sealing capacities. The results demonstrated that prisms containing 3D-printed and virtual capsules exhibited a higher recovery of mechanical and durability properties after cracking than the reference mortar prism.

Figure 2. Three-point bending test with CMOD device.

The maximum load that the CEM series prisms could withstand was 1.50 kN. When the crack opened to 0.2 mm CMOD, the force dropped to 0.20 kN. A further widening

of the crack to 0.5 mm CMOD resulted in a load of 0.05 kN. After 18 days, the strength recovery of the reference mortar prisms was found to be 3.74% on average.

The VIR series prisms demonstrated a maximum load capacity of 1.20 kN. At a crack width of 0.2 mm CMOD, the force was 0.30 kN. As the crack widened to 0.5 mm CMOD, the load decreased to 0.18 kN. The average strength recovery for the virtual capsule system after 18 days was determined to be 10.6%.

Similarly, the PLA series prisms showcased a maximum load capacity of 1.30 kN. At 0.2 mm CMOD, the force was 0.80 kN. The load decreased to 0.20 kN as the crack reached 0.5 mm CMOD. The average strength recovery for the PLA capsule system after 18 days was measured as 13%.

Overall, the VIR and the PLA series outperformed the CEM series regarding load recovery. The average data obtained from conducting three tests for each system increased the reliability and significance of these findings.

Furthermore, the specimens were subjected to water-flow tests to investigate their water permeability properties in the presence of self-repaired cracks. To do so, the specimens were initially provided with a cast-in hole, which could be connected to a water tank, in accordance with the setup described in [84]. The water-flow test was repeated twice at a distance of 10 days from each other: first, after 8 days of water immersion and then after 18 days of water immersion. Each time, during the water-flow tests, the water head, determined from the center of the cast-in hole to the upper water level in the tank, was maintained at a constant during the measurements at (50 $\pm$ 0.5) cm by periodically refilling the tank with demineralized water (Figure 3). In this way, the pressure was always kept constant at ~0.05 bar. A PC was connected to a balance (Exacta Optech 7000) to record the amount of water Δm leaked out of the crack mouth during an interval of time Δt of at least 6 min (before the tests, the lateral faces of the crack were previously sealed with silicone to ensure that the water could leak out of the specimen only through the crack mouth).

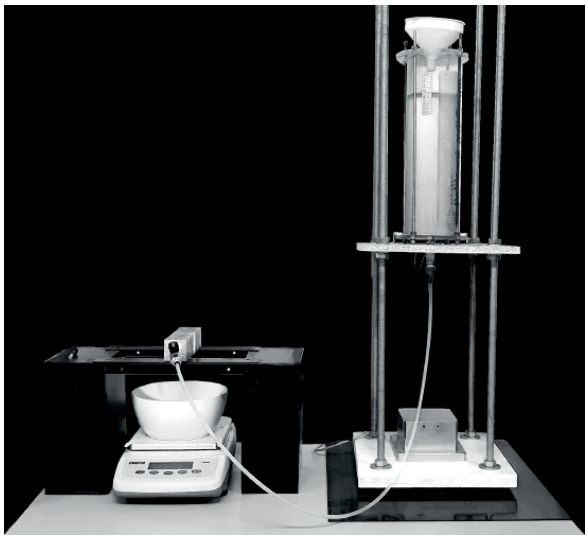

Figure 3. Water-flow test.

The water flow (*WF*) was then calculated according to Equation (5), and the sealing efficiency (*SE*) was determined by dividing the difference between the average water flows from the reference prisms and the self-healing (PLA or VIR) prisms by the water flow of the reference prisms, as reported in Equation (6). (Notice that, in this equation, SH is equal to PLA or VIR according to the case. Further, notice that, in the same equation, the term WF_{CEM} is updated for each test.) The sealing efficiency was expressed as a percentage.

$$WF = \frac{\Delta m}{\Delta t} [\mathrm{g/min}] \quad (5)$$

$$SE = \frac{WF_{CEM} - WF_{SH}}{WF_{CEM}}[\%] \quad (6)$$

The second water-flow test, conducted after 18 days of water curing, revealed that the reference samples exhibited an average reduction of 4% in water flow over a period of 10 days. This is considered a very minor autogenous healing effect that could not effectively prevent water passage through the crack.

In contrast, the PLA series prisms showed an average reduction of 25% in water flow over ten days. The sealing efficiency with respect to the reference series CEM was found to increase from 87.09% at the first execution of the water-flow test (after 8 days of water curing) to 90.30% at the second execution of the water-flow test (after 18 days of water curing), on average. These findings demonstrated that the PLA capsules significantly improved the sealing efficiency, effectively reducing the amount of water passing through the crack.

Lastly, the VIR series prisms exhibited an average reduction of 8% in water flow over ten days, with an average sealing efficiency at the end of the 18-day water curing of 96.14%. These results indicated that the virtual capsules were the most effective in preventing the passage of water through the crack.

Comparatively, both the PLA and VIR prisms demonstrated significant improvements in sealing effectiveness compared to the cement prisms. This suggests that the self-healing capsules enhance mechanical performance and improve the ability to prevent water infiltration. These findings have important implications for applying self-healing materials in construction, particularly in areas prone to water damage, such as basements or foundations.

5. Application and Results

In this section, the methodology described in Section 3 is applied to the case study presented in Section 4. The specific assumptions and results obtained are illustrated in the sub-sections below.

Notice that in this work, it is assumed that the experimental results obtained with reference to the mortars are also reproduced with the use of concrete. Thus, the properties obtained with this study, as illustrated in Section 4, are extended to the structural concrete, and the calculations are conducted according to this assumption.

5.1. Economic Evaluation via LCC: Assumptions

According to Equation (3) illustrated in Section 3.1, the economic indicator Global Cost is calculated by assuming the following set of input data, referred to as the three alternative solutions: CEM, VIR, and PLA (see Table 1). Notice that the economic assumptions and the financial data adopted for the simulation are hypothesized by considering that, for the time being, empirical evidence is not available, and, similarly, the production process is still in its early explorative stages. Further, the solely "relevant" cost items are considered, according to the norms, specifically ISO 15686:2008—part 5 related to the LCC methodology, and CEN 15459:2007 related to the Global Cost calculation. The relevant cost concept implies that (1) the modeling of the costs is effectively capable of differentiating the comparison between the technological options, (2) it omits cost items that can be considered shared among the alternatives, and (3) the relevant cost is referred to the items impacting the service life and the durability behavior of the components analyzed. Thus, we assume the following:

- The initial investment costs C_I, assumed at year 0, which include the costs of normal/self-healing wall construction [EUR/m^2], are calculated using the specific price lists based on market prices. The price list provided by the Piedmont Region, "Per opere e lavori pubblici", was used to obtain the price of a reference concrete wall. The following were used for the calculations:

- 01.A04.B05 Concrete prepared on site with 300 kg of cement type 32.5 R, 0.4 m^3 of sand, and 0.8 m^3 of gravel, supplied on site, not to be used for structural purposes, 217 EUR/m^3;
- 01 01.A04.B15 Concrete for non-structural use prepared at a dosage with cement type 32.5 R in a central concrete batching plant, with the maximum nominal diameter of an aggregate being 30 mm, supplied on site, excluding the casting, vibration, scaffolding, formwork, and iron reinforcement, and counted separately;
- 01 01.A04.B15.010 Concrete performed with 150 kg/m^3 has a value of 108.43 EUR/m^3.

By grouping both price list items, the average value obtained from the two different mixes of concrete, in which 32.5 R cement was used, is approximated to 150 EUR/m^3.

- The costs during the holding period, specifically inspection and maintenance [EUR/m^2/yr]. The analysis found on the assumption (hypothetical) that a self-healing concrete wall of the same dimensions as a normal concrete wall (1 m height × 1 m large × 30 cm width) would have a maintenance cost of EUR 25/year, which is a 50% reduction from the average maintenance cost of EUR 50/year for a normal concrete wall in Italy.
- The period of analysis, which is assumed equal to 50 years, is usually considered in the literature on the topic. This represents the following: (1) the RSL implied in the assessment of the ESL via the Factor Method, as described in Section 5.2; (2) the basis for the residual value calculation of the technical component in the function of the component's durability increment (in terms of additional service life).
- The discount rate, which is defined coherently with the literature, is assumed considering that the evaluation of the financial profitability of the investment is not the aim of the simulation. Thus, as usually carried out in LCC applications, the market risk is not included, the inflation rate is considered very low, and a high-level discount rate is excluded in the presence of a long-time period of analysis.

Table 1. LCC data assumptions.

Input Data	Unit	Option CEM	Option VIR	Option PLA
Initial investment costs	EUR /m^2	150	200	200
Annual maintenance costs	EUR/m^2/yr	50	25	25
Period of analysis	years	50	50	50
Discount rate	%	3%	3%	3%

5.2. Service Life Estimation via the Factor Method: Assumptions

According to the methodology, a 50-year RSL is assumed as the first step. Then, the sub-factors capable of influencing the durability of the component are selected based on the available laboratory test results: specifically, factor A (quality of materials and components), detailed with the sub-factors Max Load, Resistance at 0.2 mm CMOD, Resistance at 0.5 mm CMOD, Strength Recovery, and factor G (maintenance level), detailed with the sub-factors Water-flow (L/min) variation in 10 days, and Sealing effectiveness (steel reinforcement protection) in 10 days.

Once the RSL was determined and the sub-factors were selected to influence the durability of the component, the ESL is calculated using the following Equation (7), derived from Equation (4):

$$ESL = RSL \times A_1 \times A_2 \times A_3 \times A_4 \times B \times C \times D \times E \times F \times G_1 \times G_2 \quad (7)$$

where ESL stands for the Estimated Service Life, RSL stands for the Reference Service Life, A_1, A_2, A_3, and A_4 stand for the sub-factors related to factors A, and G_1 and G_2 stand for the sub-factors related to factor G.

Notice that, in weighing the influence of the sub-factors, a mean value is calculated to quantify a synthetic weight of the factor as a whole. Thus, the final Equation results as follows:

$$ESL = RSL \times \overline{A}_{1,2,3,4} \times B \times C \times D \times E \times F \times \overline{G}_{1,2} \quad (8)$$

The quantification of the sub-factors is conducted by assigning a value k to each factor, within a range of 0.8–1.2 pts., as suggested in the norm and literature [38,67], and starting from the results of laboratory tests, which are opportunely weighed using an ordinary scale (0–5 pts.). Further, considering the uncertainty in the data assumptions due, for example, to the market price variability, flexibility in the model is introduced by simulating a variation in the k values within a range of 0.9–1.1 pts. For simplicity, the first option (0.8–1.2 pts.) is named the "high impact scenario", and the second one (0.9–1.1 pts.) is named the "low impact scenario" (see Table 2).

Table 2. Test report and weighting scales.

Scale: 0–5 pts.	Scale: 0.8–1.2 pts. High Impact Scenario	Scale: 0.9–1.1 pts. Low Impact Scenario
0	0.8	0.9
1	0.88	0.94
2	0.96	0.98
3	1.04	1.02
4	1.12	1.06
5	1.2	1.1

The test results were compared on a 0–5 pts. scale for the three options, CEM, VIR, and PLA, are synthesized in Table 3.

Table 3. Test report: summary table.

Tests	Option CEM	Option VIR	Option PLA
Max Load (kN)	5	4	4.33
Resistance at 0.2 mm CMOD	1.25	1.875	5
Resistance at 0.5 mm CMOD	1.25	4.5	5
Strength Recovery	1.43	4.07	5
Water flow (liters/minutes) variation in 10 days	0.8	1.6	5
Sealing effectiveness (steel reinforcement protection) in 10 days	0	5	4.5

The weights assigned to the selected factors A and G and the related sub-factors are represented in the tables below. Notice that the factors B, C, D, E, and F are not objects of specific analyses in relation to specific sub-factors, at least at this step of the research, and, thus, their weight is assumed to equal 1. To complete the analysis and assume that even a slight variation in input data can significantly influence the ESL and, consequently, the durability of the components, the analysis is repeated with two different ranges of weights, according to the previously mentioned hypothesis. Thus, a "low impact" scenario and a "high impact" scenario are implemented. The results are illustrated in Table 4.

Table 4. Sub-factor weighting.

Factors	Sub-Factors	k	Option CEM	Option VIR	Option PLA
a. High impact scenario.					
A Quality of the construction materials	Max Load (kN)	K_1	1.2	1.12	1.146
	Resistance at 0.2 mm CMOD	K_2	0.9	0.95	1.2
	Resistance at 0.5 mm CMOD	K_3	0.9	1.16	1.2
	Strength Recovery	K_4	0.914	1.126	1.2
Mean A values			**0.978**	**1.089**	**1.187**
G Maintenance level	Water flow (L/min) variation in 10 days	K_1	0.864	0.928	1.2
	Sealing effectiveness (steel reinforcement protection) in 10 days	K_2	0.8	1.2	1.160
Mean G values			**0.832**	**1.064**	**1.180**
b. Low impact scenario.					
A Quality of the construction materials	Max Load (kN)	K_1	1.1	1.06	1.073
	Resistance at 0.2 mm CMOD	K_2	0.95	0.975	1.1
	Resistance at 0.5 mm CMOD	K_3	0.95	1.08	1.1
	Strength Recovery	K_4	0.957	1.063	1.1
Mean A values			0.989	1.044	1.093
G Maintenance level	Water flow (L/min) variation in 10 days	K_1	**0.932**	**0.964**	**1.1**
	Sealing effectiveness (steel reinforcement protection) in 10 days	K_2	0.9	1.1	1.080
Mean G values			**0.916**	**1.032**	**1.090**

5.3. Simulations and Results

Based on the data set described in the previous sections, the Global Cost application is operated for the three options, and then, the results are compared.

The ESLs are calculated using the Factor Method for each option as a first step, obtaining the results summarized in Table 5 below.

Table 5. ESL calculation for CEM, VIR, and PLA. Low impact scenario and high impact scenario.

	ESL—High Impact	ESL—Low Impact
	Years	**Years**
Option CEM	40.71	45.31
Option VIR	57.93	53.90
Option PLA	70.00	59.58

As highlighted in Table 5, the ESL for the CEM option shows a significant decrease in both the high impact and low impact scenarios, with a decrease from 5 to 10 years for the low and high impact scenarios. An opposite behavior is demonstrated for the VIR and PLA alternatives, which show an increase in the ESL, going from almost 4 years for the scenario VIR (low impact) to 20 years for the scenario PLA (high impact).

Assuming these quite divergent results, different LCC models are implemented by monetizing the respective residual values of the components.

In summary, by applying the LCC model for the whole set of options, the following results are obtained (see Table 6). The summary table presents the Net Present Values

(NPVs) calculated for the three alternatives, CEM, VIR, and PLA, for high and low impact scenarios.

Table 6. NPV calculation for CEM, VIR, and PLA. Low impact scenario and high impact scenario.

	NPV—High Impact	NPV—Low Impact
	EUR	EUR
Option CEM	−1424.31	−1428.58
Option VIR	−843.67	−840.72
Option PLA	−850.46	−844.76

The NPVs obtained demonstrate a remarkable variability in view of the material adopted, ranging from the solution with the highest cost of the scenario CEM, with very close results for high and low impact scenarios, up to the alternatives VIR and PLA, which show significant reductions in the costs for both high and low impact scenarios.

Despite the simplicity of the simulation, the results demonstrate a remarkable convenience in adopting self-healing solutions, according to an economic perspective, due to the capability of innovative materials to improve the service lives and, as a consequence, the durability of components and their residual values. Further, the decrease in maintenance investments and repair contributes to containing the costs amounts during the holding period.

6. Conclusions

This paper proposes a methodology to verify from the economic viewpoint, focusing on the efficiency of self-healing concrete solutions as an alternative to traditional concrete. More generally, the methodology aims to support decision making in selecting the preferable solutions with alternative material components. Assuming that the results of research previously implemented to experimentally develop the components are accurate, in this research, the focus is posed on the life-cycle cost calculation and residual value as relevant items capable of orienting the design and investment decisions in the building and construction sector.

According to a circular perspective, the LCC analysis is proposed for quantifying (and comparing) each solution's synthetic economic indicators (NPVs). The LCC model is applied jointly with the Factor Method as an approach capable of supporting the service life estimation of components according to a performance approach. More precisely, applying the Global Cost method, the life-cycle cost of three alternative components is quantified in monetary terms, internalizing into the model alternative service lives and related potential residual values.

The methodology is experimented with assuming a case study based on comparing self-healing concrete systems using capsule strategies. Precisely, a traditional concrete wall (CEM) is compared with two self-healing concrete walls based on two capsule types: 3D-printed ones sealed with an epoxy resin (PLA) and Virtual Capsules formed by compacting an active powder mix at high temperatures (VIR). The hypothesis to use these materials in building construction in Northern Italy is assumed. Notice that, as underlined in Section 5, in this work, it is assumed that the experimental results obtained with reference to the mortars can be extended to the concrete, and the calculations are conducted according to this assumption.

The study results demonstrate the advantage in evaluating the preferability of alternatives in the whole project life cycle, including jointly technological and economic effects. Assuming the capability of lifespan to influence the total life-cycle cost calculation, the results give full evidence of the potential benefits due to the use of self-healing materials in the construction sector via the reduction in component maintenance costs, the increase in durability, and related residual values. Consequently, benefits are obtainable from the capacity to reduce environmental impacts.

Despite the results obtained and the simplicity of the applied method, some limitations emerge from the research. For example,

- The financial assumptions should be verified, specifically concerning the discount rate adopted, the initial and maintenance cost amounts, etc.;
- The Factor Analysis, with the use of sub-factors, is related to only two factors over seven, and it should be completed by considering the specific sub-factors for each factor adopted;
- The application of the analysis is related to a single reference component, and it should be extended to a larger reference scale, considering a whole building;
- The stochasticity in data assumptions could introduce uncertainty in the model, which could then be solved via probabilistic analysis.

Future directions of this research could start from these limitations to improve the contribution to growing the literature on this topic.

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Abbreviations

LCC:	Life-Cycle Costing
FM:	Factor Method
RSL:	Reference Service Life
PPP:	Private Public Partnership
PLA:	Polylactic acid
VIR:	Virtual capsules
CMOD:	Crack Mouth Opening Displacement
WF:	Water Flow
SE:	Sealing Efficiency
ESL:	Estimated Service Life
NPV:	Net Present Value

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